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SPECTRAL GROWTH OF HURRICANE GENERATED SEAS

By

WILLIAM SCOTT FINLAYSON

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

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SPECTRAL GROWTH OF HURRICANE GENERATED SEAS

By

William Scott Finlayson

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Chairman: R. M. K. Ochi
Major Department: Coastal and Oceanographic Engineering

The characteristics of a growing sea during hurricanes are significantly different from those observed in ordinary storms since the source of energy generating waves is moving and the rate of change of wind speed is very fast. This thesis presents the results of a study on the growth of sea severity during hurricanes with the aid of a wave spectral formulation representing the associated sea conditions. Through analysis of spectra obtained from wave data during the growing stage of five hurricanes, it is found that the Modified JONSWAP spectral formulation well represents field data over a wide range of frequencies. This enables us to evaluate the general trend of the growth of a hurricane generated sea by applying the Modified JONSWAP spectrum. The two parameters (significant wave height and modal frequency) involved in the Modified JONSWAP spectrum are presented as a function of wind speed which permits the presentation of the growth of the wave spectrum as a function of wind speed. It is found that, during the

growing stage of a hurricane, the increase in wave energy in the neighborhood of the modal frequency is much greater than that at any other frequency of the spectrum.

CHAPTER 1
INTRODUCTION

The purpose of this study is to evaluate the wave spectral energy growth of hurricane associated seas. The best approach to achieve this goal is to analyze the shape of wave spectra obtained from measured data at various stages of hurricane growth. However, it is difficult in practice to derive a general conclusion by evaluating the difference in the magnitude of energy for a specified wave frequency at different stages of growth. One way to overcome this difficulty is to evaluate the growth of wave energy through spectral formulation. It is then necessary to have a wave spectral formulation which represents well the wave energy spectrum throughout the growing stage of hurricanes. A good candidate is the Modified JONSWAP formulation developed by Foster (1982) and Ochi (1993). However, the Modified JONSWAP formulation must be verified to confirm it is valid over the entire frequency domain of the wave energy spectrum for hurricane generated seas.

In order to use the Modified JONSWAP formula as the basis for evaluating the growth of hurricane associated wave spectra, it is highly desirable to examine the validity of the spectral formulation over the entire frequency domain. The subject is discussed in detail in Chapter 3. A brief explanation of the Modified JONSWAP formulation for wave spectra for hurricane generated seas is given. Most importantly, the Modified JONSWAP formula is verified throughout the entire frequency domain. Also, wave

spectral data is compared to the Modified JONSWAP formulation and to existing spectral formulation to show how well it agrees with observed hurricane data.

Since the Modified JONSWAP formula is a function of significant wave height and modal frequency, and the design criterion usually specified is wind speed, a method is prescribed in Chapter 4 to estimate modal frequency and significant wave height as functions of wind speed. And therefore, growth of hurricane wave energy spectra can be estimated through the Modified JONSWAP formula.

Before analyzing wave energy spectra for hurricanes, it is useful to understand the atmospheric phenomenon which give rise to the wave energy spectra. Atlantic hurricanes, or tropical cyclones, are most often formed from tropical low pressure disturbances leaving the West Coast of Africa. The Atlantic Hurricane Season is from May to November. Large convective energy from warm water feeds these tropical cells as they are carried across the Mid-Atlantic. A characteristic Coriolis driven cyclonic rotation develops to maintain the low-pressure disturbance as the storm becomes a tropical depression. This rotation becomes more organized, the center's atmospheric pressure drops, and wind speed increases. Strengthening, the tropical depression is upgraded to a tropical storm and then to a hurricane. Based on maximum wind speeds and, to a lesser extent, on the atmospheric pressure in the eye, these storms are classified according to the Saffir-Simpson Scale given in Table 1.

Several favorable existing environmental conditions must be in place for a tropical disturbance to grow to hurricane strength. Hurricanes require warm ocean waters greater then 80° F and a large negative atmospheric temperature gradient. This temperature gradient creates an unstable condition for moist convection and drives the

Table 1 Saffir-Simpson Hurricane Scale

Type	Category	Damage	Pressure Hg (in)	Winds mph
Depression	-	-	-	>35
Tropical storm	-	-	-	39-73
Hurricane	1	minimal	>28.94	74-95
Hurricane	2	moderate	28.50-28.91	96-110
Hurricane	3	extensive	27.91-28.47	111-130
Hurricane	4	extreme	27.17-27.88	131-155
Hurricane	5	catastrophic	<27.17	>155

necessary massive thunderstorms which releases thermal-energy contained in the ocean water. Hurricanes cannot exist at distances any closer to the equator then 500 km, as a non-negligible Coriolis force is necessary to offset the low pressure disturbance. A pre-existing near-surface disturbance with sufficient vorticity and convergence is required. Tropical cyclones cannot be generated spontaneously. To develop, they require a weakly organized system with sizable rotation and low level inflow.

Although large storms can create sea-severity comparable to hurricanes, there are characteristic atmospheric features of hurricanes which differentiate them from ordinary large Atlantic storms. The low-pressure center, maintained by a Coriolis force, induces a high rate of cyclonic rotation, causing extreme localized wind speeds. In contrast, this low pressure center, known as the eye, has virtually no associated wind. The strongest hurricanes have the lowest associated central atmospheric pressure and the smallest eye

diameter. This well defined eye can be used to track the location of the storm. Although hurricanes can effect large areas, they are a local geostrophic phenomenon, driven by greater atmospheric forces. Low and high-pressure fronts move hurricanes at speeds in excess of 25 knots.

In contrast to hurricanes, ordinary storms are not as well organized and do not have an easily defined center. Consequently, their location cannot be precisely tracked. Ordinary storms are relatively stationary and have little rotation, so they are characterized as having quasi-steady, non-localized winds blowing in a general direction over an established fetch length.

To design a structure to operate in hurricane prone areas, an accurate prediction of growth of hurricane generated wave spectra at a specific location with respect to the storm is necessary. Because of differences in atmospheric characteristics, hurricanes cause wave spectra to grow differently than for ordinary storms. When characterizing hurricane associated events several factors are considered, in general, including maximum sustained winds, radius of maximum winds, central barometric pressure, distance to the storm, speed of the storm and others. However, it has been found that shape and growth of wave spectra are generally dependent upon mean wind speed measured at a known distance above the sea surface and a characteristic fetch length over which the wind is acting. It is convenient to define the fetch length as the distance from the eye to the design location.

Since hurricanes center are rapidly moving, wind speed at a fixed location and fetch length change rapidly. This extreme increase in wind speed and change in fetch length have the most profound effect on hurricane wave spectra shape and growth. In

contrast to normal wave spectra, hurricane wave spectra have a more pronounced peak at the modal frequency, where more energy is contained. This is due to the rapid increase of wind speed driving the growth. Wave energy is concentrated primarily in the neighborhood of the peak frequency during hurricanes as contrasted with the energy spread over a wide frequency range, including double peaks, for wave spectra obtained during ordinary storms (Ochi, 1993). Sea-severity cannot develop in the high frequency range as quickly as wind speed. Unlike for ordinary storms, where modal frequency clearly migrates from higher to lower frequencies during spectral growth, hurricane wave spectra grow predominately at lower modal frequencies. There is some leftward migration of modal frequency with growth, but it quickly becomes concentrated at a low frequency.

CHAPTER 2
LITERATURE SEARCH

Limited research has been done on finding a mathematical representation of hurricane wave energy spectra. Cardone, Pierson and Ward (1976), Bretschneider and Tamaye (1976), Young and Sobey (1981), Ross and Cardone (1978) and Young (1988) have carried out studies on hurricane-generated seas, primarily through hindcasting and forecasting approach. These techniques provide valuable insight, but they cannot be used to predict growth. There have been many wave spectral formulation developed to represent sea severity, none of which predict hurricane spectra well. The Pierson-Moskowitz (1964), the two parameter, the three parameter, the six parameter (Ochi and Hubble, 1976) and the JONSWAP (Hasselmenn et al., 1973) are all useful for representing ordinary wind generated seas.

Antani (1981) compared the shape of nearly 400 hurricane wave spectra to various mathematical formulations, such as the one parameter (Pierson and Moskowitz, 1964), the two parameter, the three parameter, the six parameter (Ochi and Hubble, 1976) and the JONSWAP spectra (Hasselmann et al., 1973). His results showed that the six parameter and JONSWAP most closely represent hurricane wave spectra shape. The JONSWAP is a better candidate in that it produces a single spectrum and was developed based on fetch limited data. It has also been suggested as the formulation of choice for hurricanes by Lee (1980), Ross(1976), and Whalen and Ochi (1978).

Foster (1982) and Ochi (1993) developed a Modified JONSWAP formula. They analyzed data from several hurricanes and represented the original JONSWAP coefficients in terms of significant wave height and modal frequency. Ochi (1993) compared the Modified JONSWAP formula to wave spectra data from several hurricanes and showed that it was a good representation of the hurricane associated wave spectrum.

CHAPTER 3
SPECTRUM FORMULATION REPRESENTING HURRICANE GENERATED SEAS

As stated in Chapter 1, the Modified JONSWAP spectral formula will be used as the basis for evaluating wave spectral growth for hurricane generated seas is to have a wave spectral formulation which represents hurricane generated seas at various stages of growth. The Modified JONSWAP formulation was derived based on peak energy hurricane data and seems to represent hurricane wave spectra well. It is important to validate the Modified JONSWAP formula over the entire frequency domain at various stages of hurricane growth in order to determine how well it represents hurricane generated seas.

Verification of Modified JONSWAP Spectrum

Ochi and Foster have done considerable work in determining the coefficients for the JONSWAP spectral formulation for hurricane generated seas. A limited explanation is provided here to outline the process used and to illustrate assumptions made during the derivation. For a complete understanding of the determination of these parameters the reader is directed to Foster (1982) and Ochi (1993).

The original JONSWAP formulation is given by

$$S(f) = \alpha \frac{g^2}{(2\pi)^4 f^5} \exp\left\{-1.25\left(\frac{f_m}{f}\right)^4\right\} \gamma^{\exp\left\{-\left(\frac{f}{f_m}-1\right)^2 / 2\sigma^2\right\}} \tag{1}$$

where. γ = peak shape parameter, 3.30 as an average

$\alpha = 0.076\,(x)^{-0.22}$

$\sigma = 0.07$ for $\omega \leq \omega_m$ and 0.09 for $\omega > \omega_m$

$f_m = 3.5\,(g/U)(x)^{-0.33}$

x = dimensionless fetch = gr/U^2

r = fetch length

U = mean wind speed

Foster analyzed the values of the parameters in the original JONSWAP formulation, Equation (1), and determined functional relationships for α and the peak shape parameter, γ. The parameter α is a function of dimensionless fetch length and, due to the rapidly changing wind speeds, is difficult to evaluate for hurricanes. However, analysis showed α can be presented as the function of significant wave height, H_s, and modal frequency, f_m, given in Equation (2) (Foster, 1982). The constant, α, carries the units of $(\mathrm{sec}^2/\mathrm{meter})^2$.

$$\alpha = 4.5 H_s^2 f_m^4 \tag{2}$$

The peak energy, $S(f_m)$, of the hurricane data was determined by analyzing $S(f_m)$ as a function of H_s and found to be represented by

$$S(f_m) = 0.75 H_s^{2.34}\ . \tag{3}$$

The peak energy, at $f=f_m$, of the JONSWAP spectrum is determined from Equation (1) and is given as

$$S(f_m) = \alpha \frac{g^2}{(2\pi)^4 f_m^5} \exp(-1.25)\gamma \ . \tag{4}$$

From Equations (2) through (4) the peak shape parameter, γ, can be shown to be a function of significant wave height, H_s, and modal frequency, f_m, as

$$\gamma = 9.5 H_s^{0.34} f_m \ . \tag{5}$$

It is noted that γ was determined using peak spectral energy, which is a key feature of this derivation. Using these relationships Equation (1) can be written as a function of ω as

$$S(\omega) = \frac{4.5}{(2\pi)^4}(H_s g)^2\left(\frac{\omega_m^4}{\omega^5}\right)\exp\left\{-1.25\left(\frac{\omega_m}{\omega}\right)^4\right\}\left(\frac{9.5}{2\pi}H_s^{0.34}\omega_m\right)^{\exp\left\{-\left(\frac{\omega}{\omega_m}-1\right)^2 / 2\sigma^2\right\}} \tag{6}$$

where $\sigma = 0.07$ for $\omega \leq \omega_m$ and 0.09 for $\omega > \omega_m$.

Equation (6) will be referred to as the Modified JONSWAP formulation. It was developed by determining γ from data at the modal frequency. Consequently it is highly desirable to confirm the formulation is valid over the entire frequency domain of the spectrum through comparison with measured data.

In order to compare spectra to each other having various modal frequencies, the frequency range for each energy density spectrum used for the current study was normalized by dividing by modal frequency, ω_m. Each spectrum was then broken into sections from ω/ω_m=0.80 to ω/ω_m=2.35 at intervals of 0.05. Figure 1 demonstrates the procedure. The result gives values of spectral energy, $S(\omega)$, known for each spectrum at 80% to 235% of the modal frequency, at 5% intervals. The corresponding values of

spectral energy for each ω/ω_m, are plotted versus significant wave height in Figures 2 through 34.

On each figure is a plot of the Modified JONSWAP formula at corresponding normalized modal frequencies. The figures illustrate how well the Modified JONSWAP formula represents hurricane data taken during the growing stage at various sea severities (significant wave heights) throughout the frequency domain. The figures demonstrate the utility of the Modified JONSWAP formula. Even though derived by analyzing peak spectral energy (ω/ω_m=1.00, Figure 6), it agrees reasonably well with values of spectra data throughout the normalized frequency domain. Figure 27 shows even at twice the modal frequency, the Modified JONSWAP formula adequately agrees with data. At ω/ω_m>2.00 the data begins to scatter but the magnitude of $S(\omega)$ is substantially reduced in comparison with that at the peak frequency.

Comparison with Wave Spectra obtained from Measured Data

Although some examples of comparison between the wave spectra obtained from wave data during hurricanes and the Modified JONSWAP spectral formulation are given in the references (Ochi 1993, for example) it may be of considerable interest to show comparisons at various stages of hurricane intensities. Included in the comparisons are the Pierson-Moskowitz and the two parameter formulations. Since these formulations were developed for ordinary wind generated sea it may be of interest to examine how well they represent hurricane generated sea conditions. Figures 34 through 44 show comparison between selected data to the Modified JONSWAP formulas.

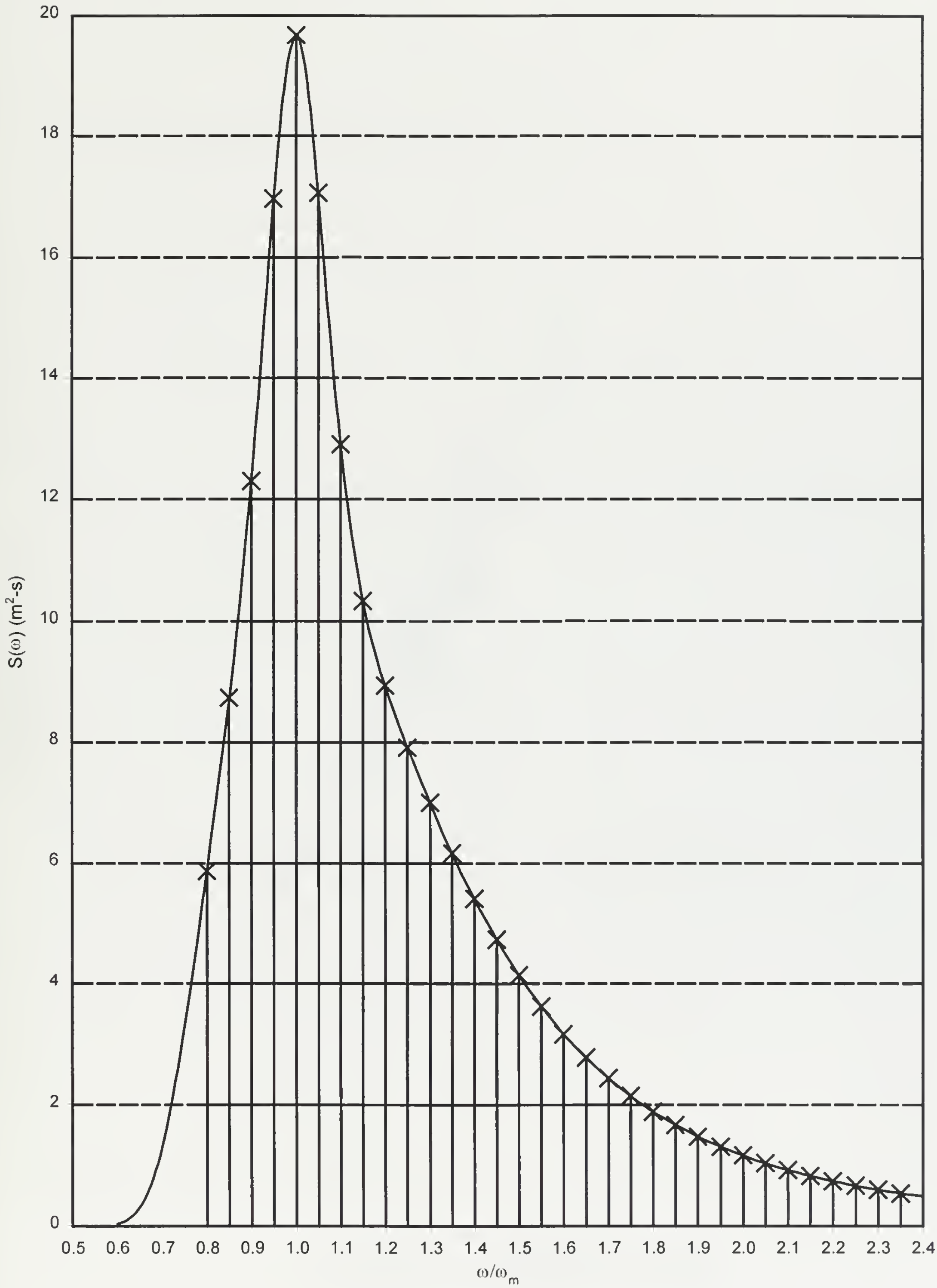


Figure 1 Representative data wave energy spectrum normalized by ω_m and analyzed piecewise for intervals of ω/ω_m of 0.05

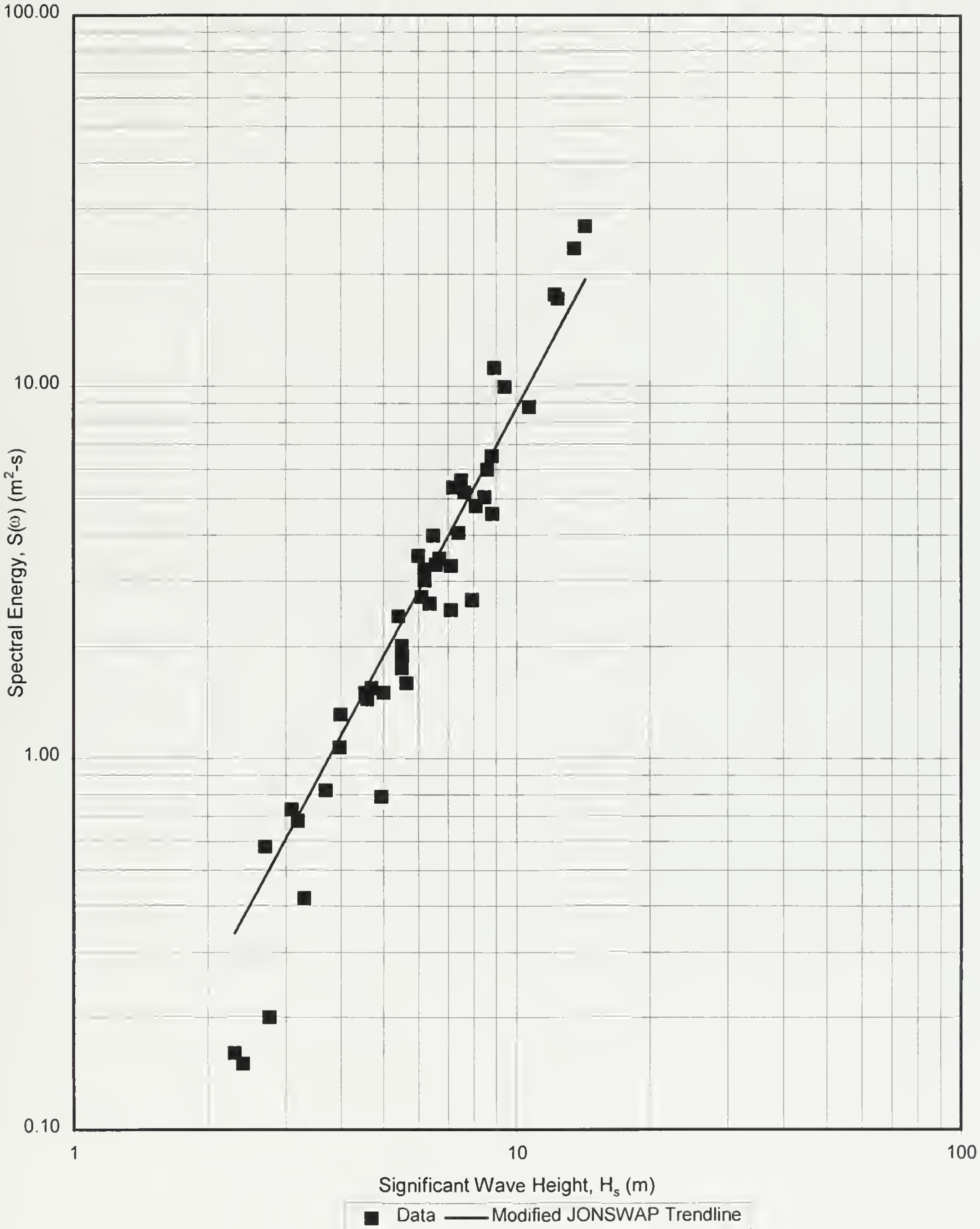


Figure 2 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=0.80

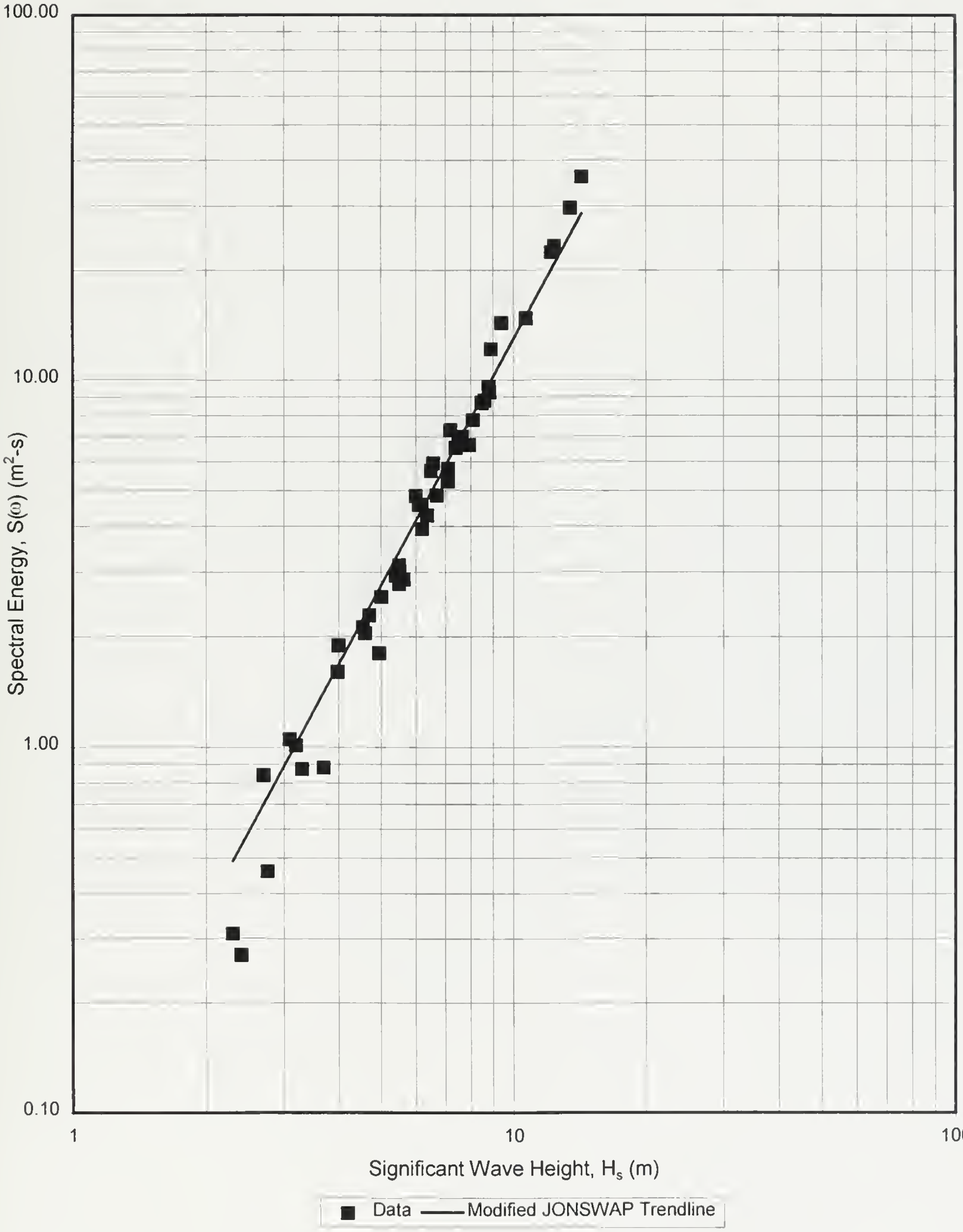


Figure 3 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=0.85

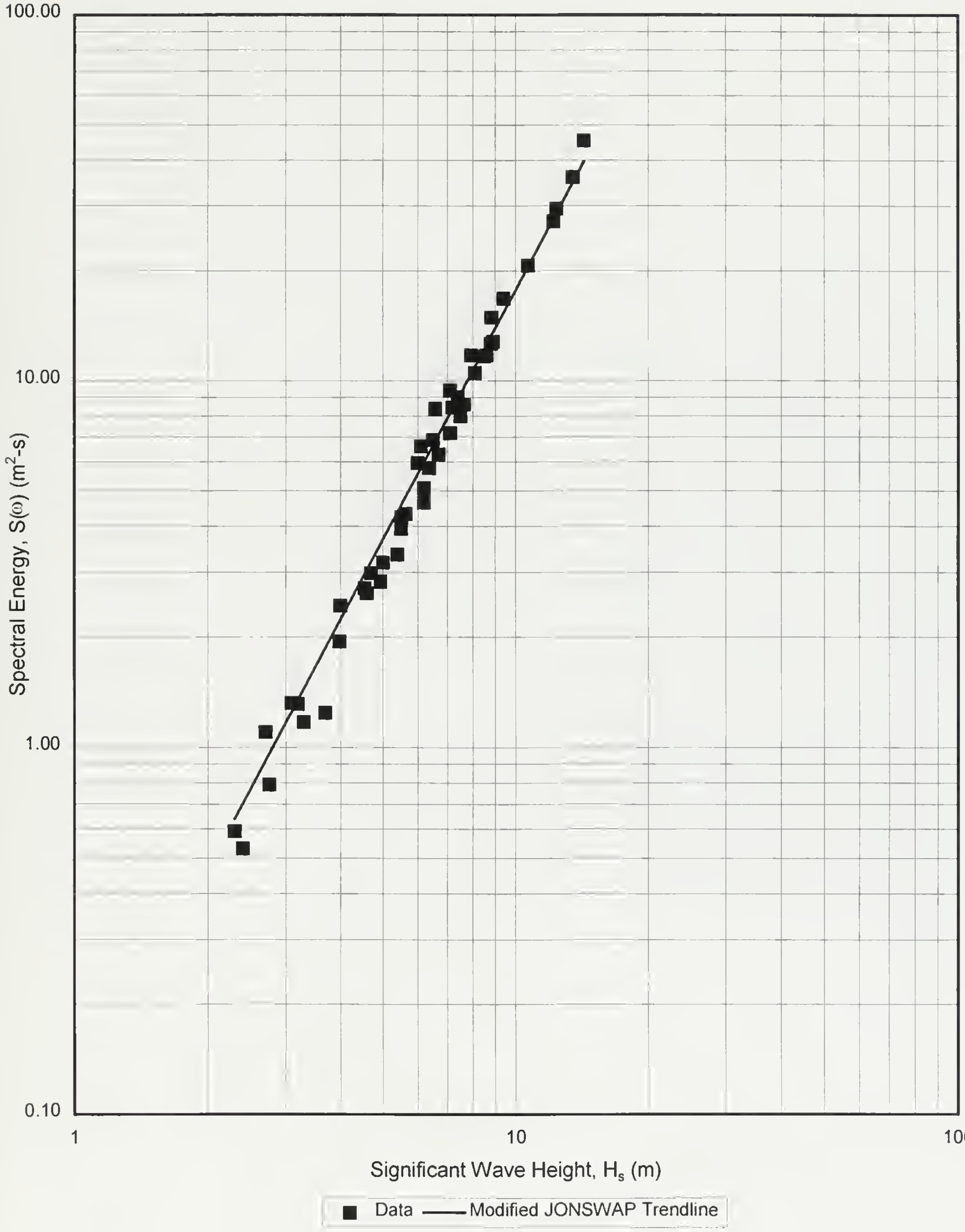


Figure 4 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=0.90

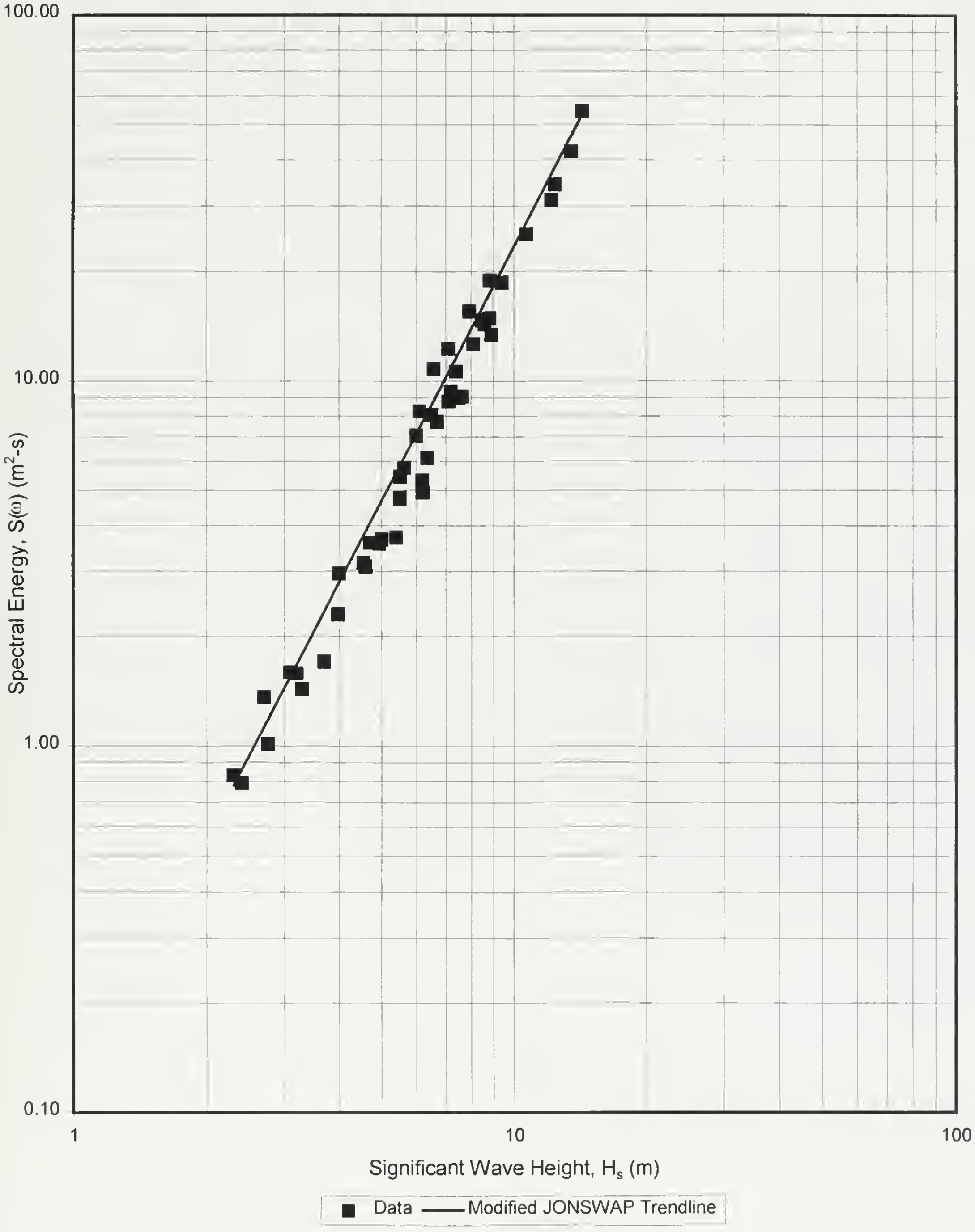


Figure 5 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=0.95

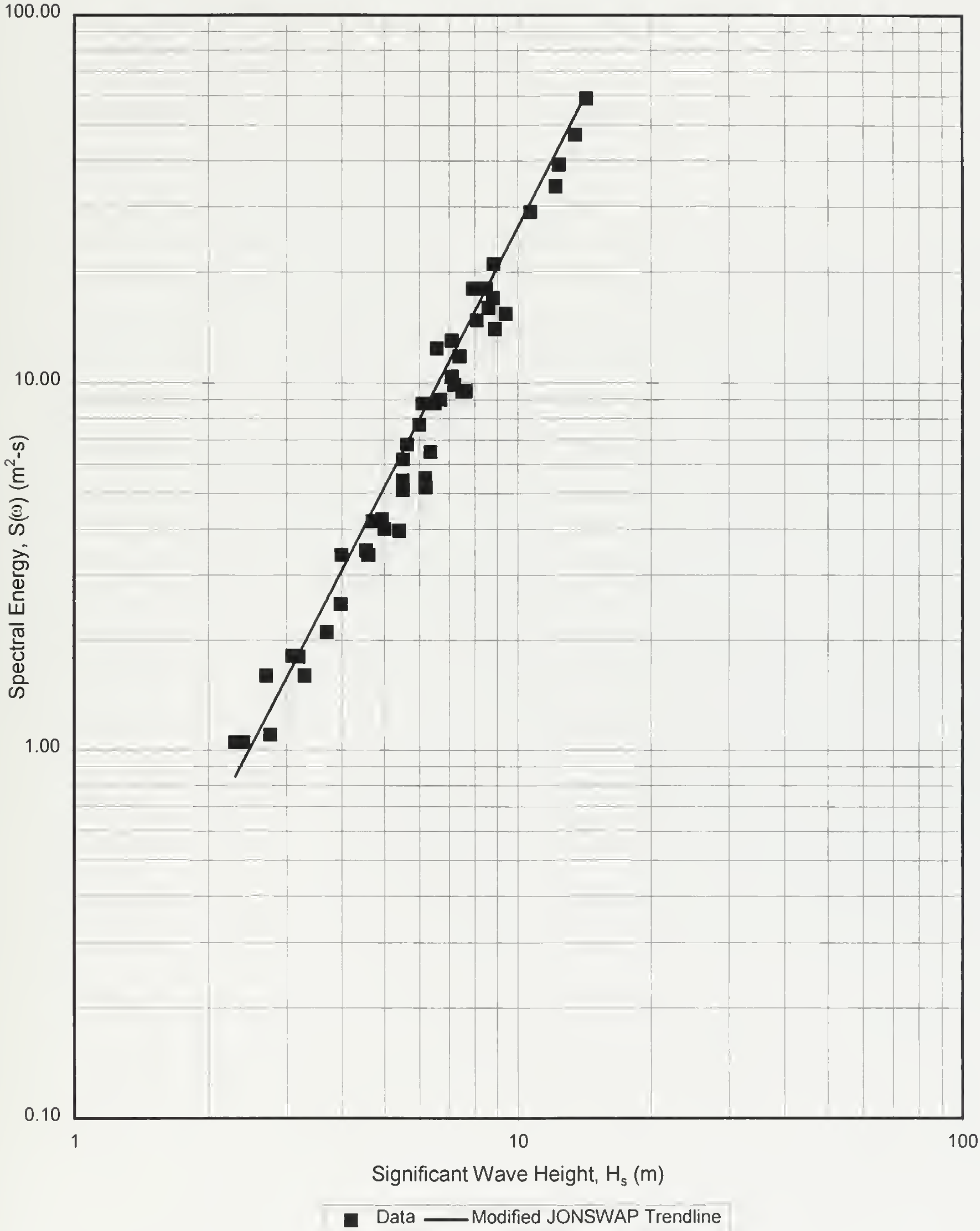


Figure 6 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.00

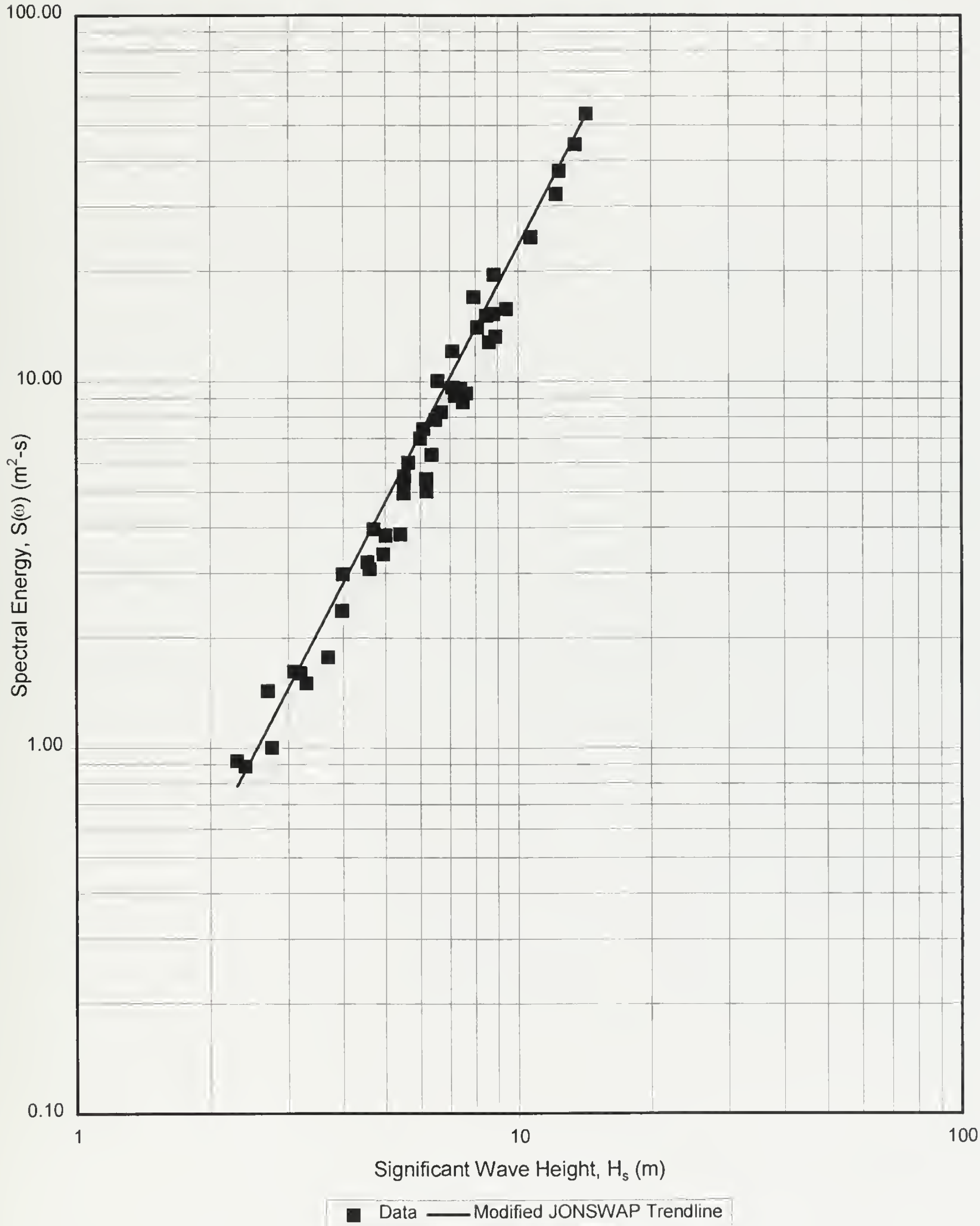


Figure 7 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.05

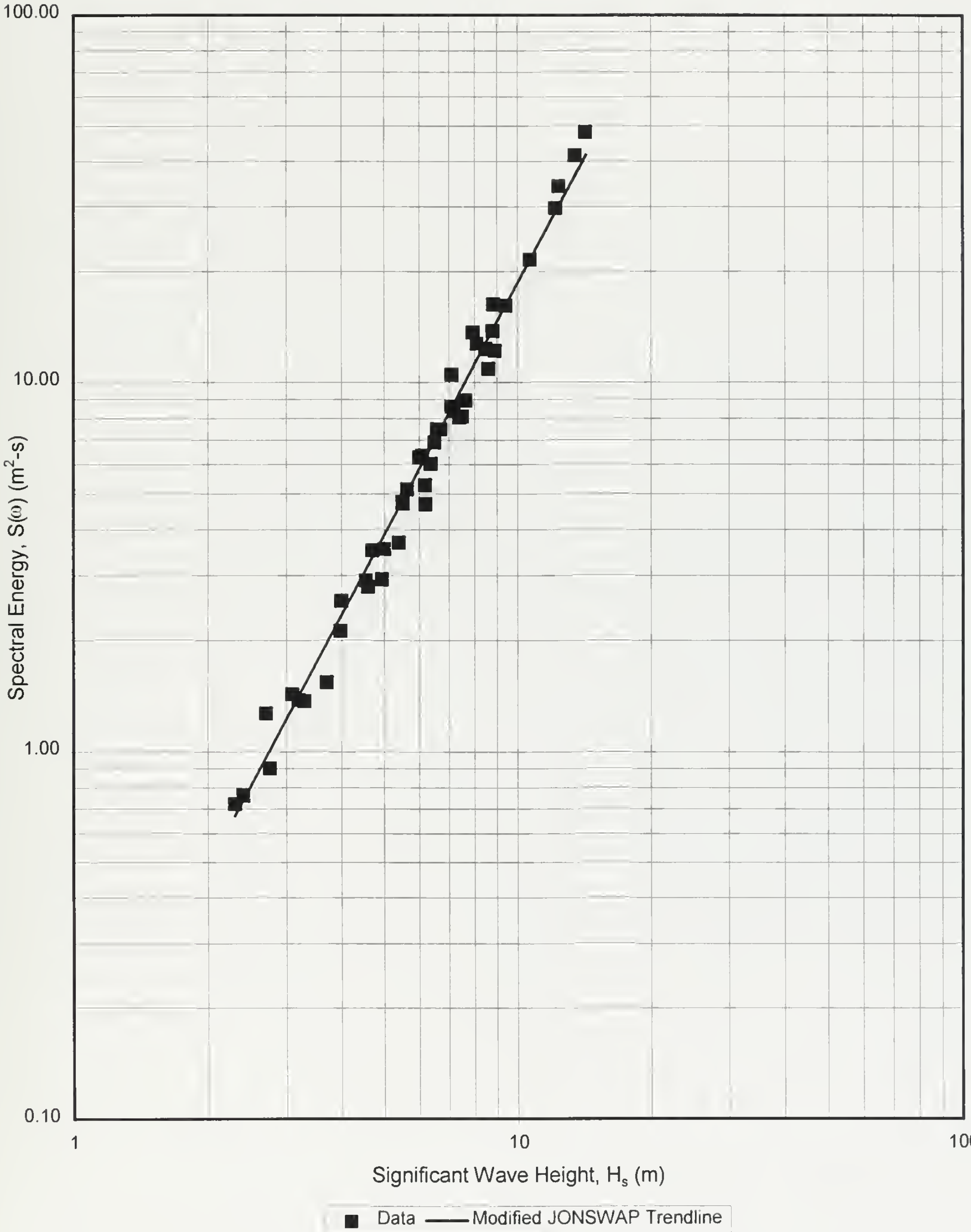


Figure 8 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.10

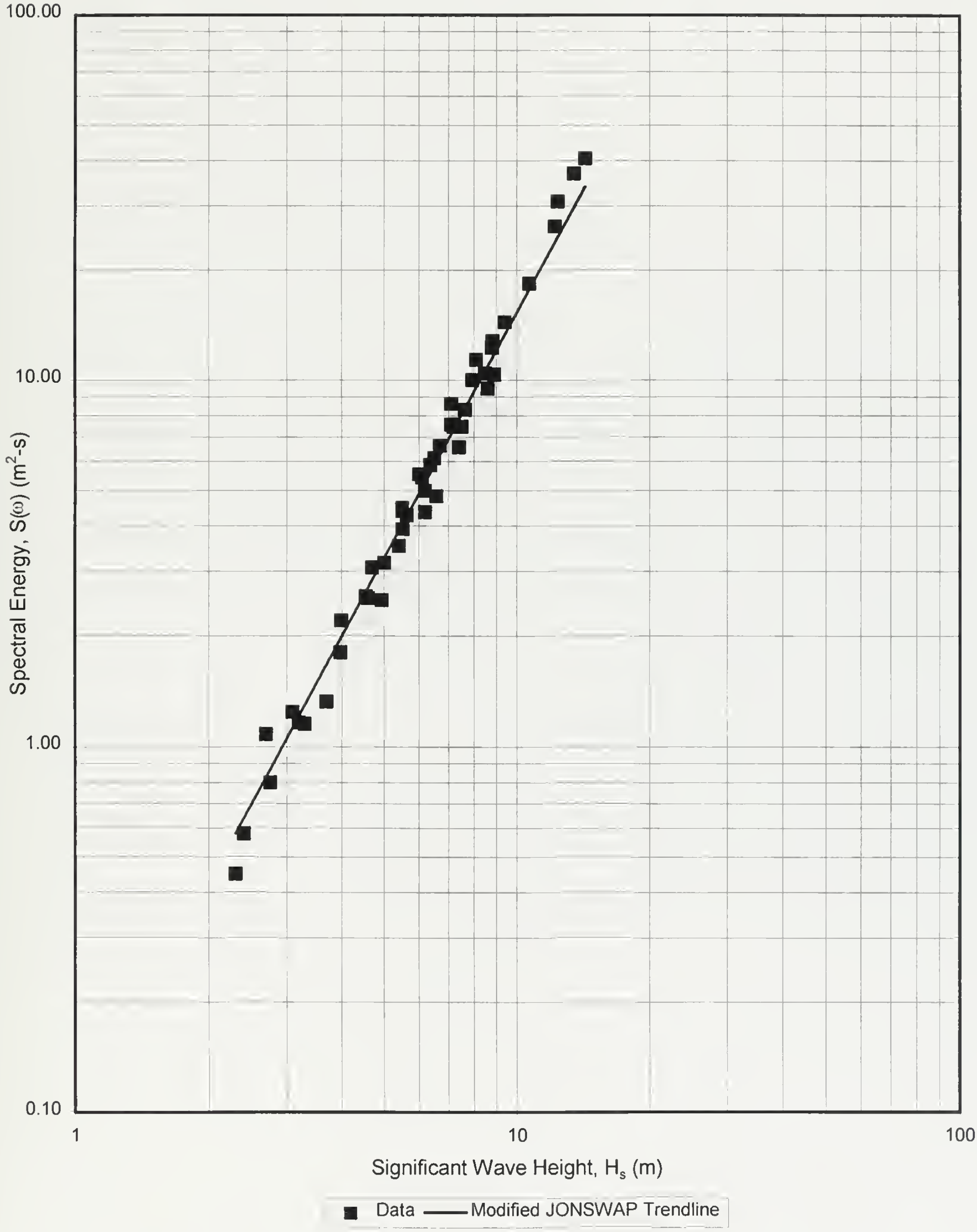
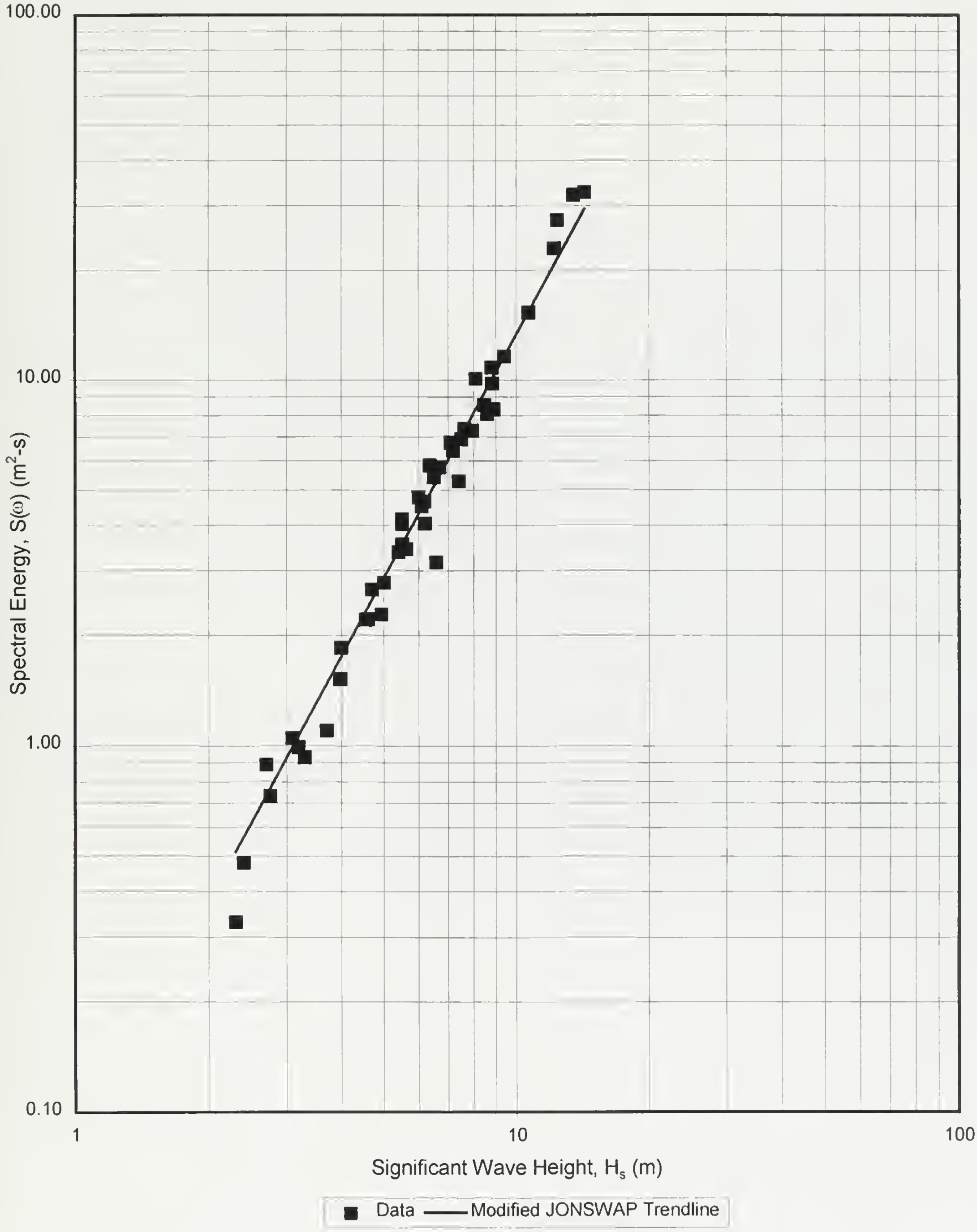


Figure 9 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.15



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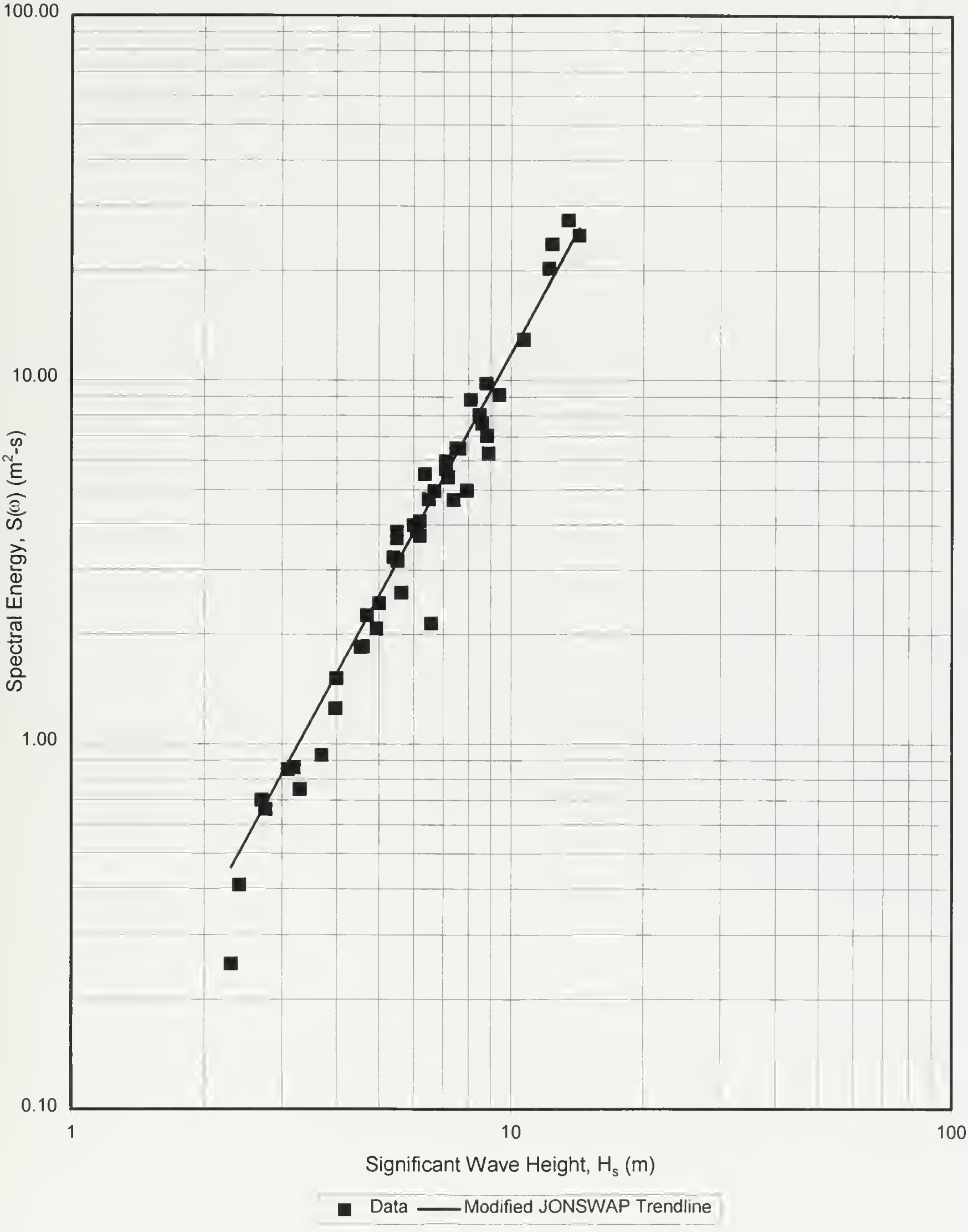
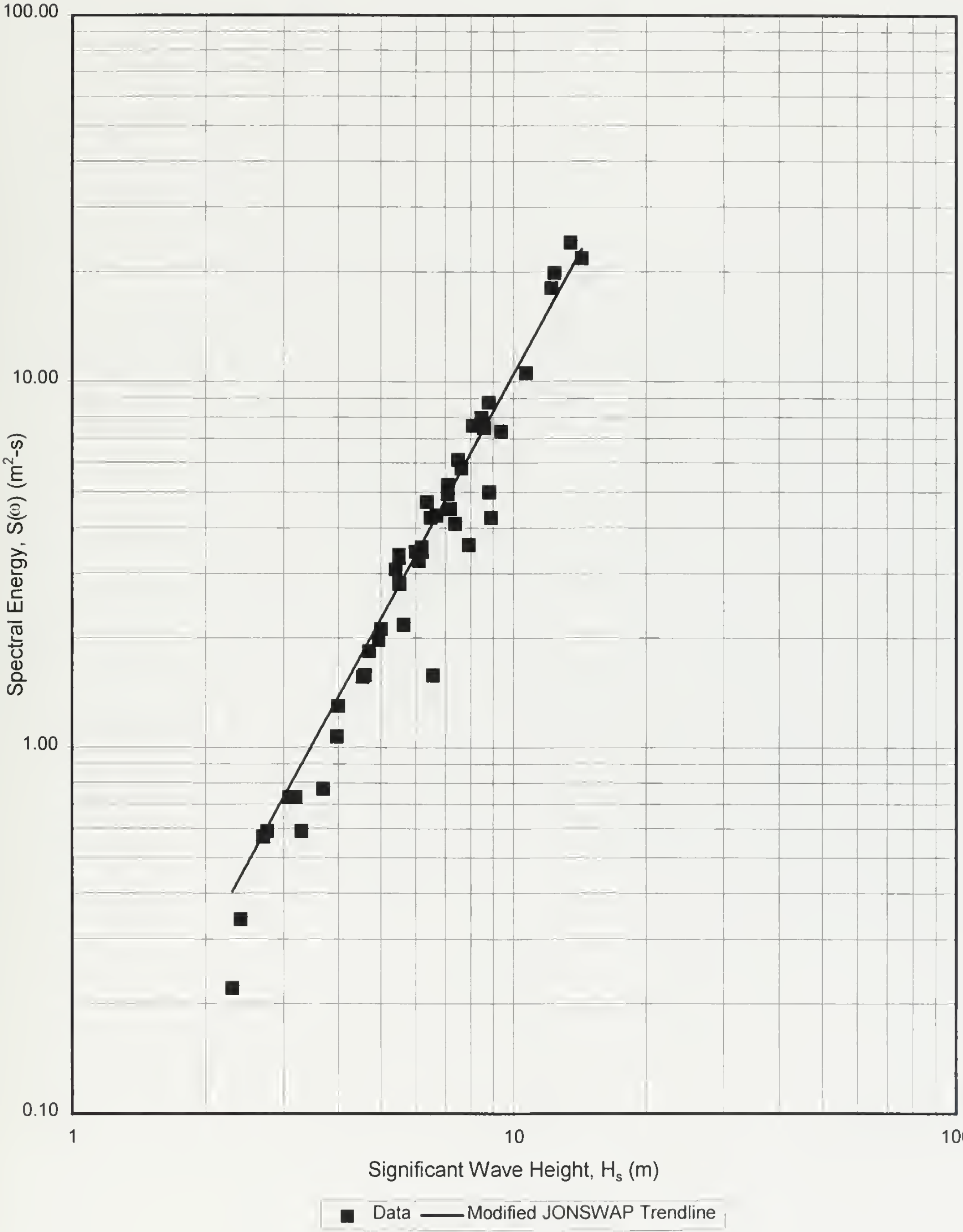


Figure 11 Modified JONSWAP spectrum versus significant wave height for $\omega/\omega_m=1.25$



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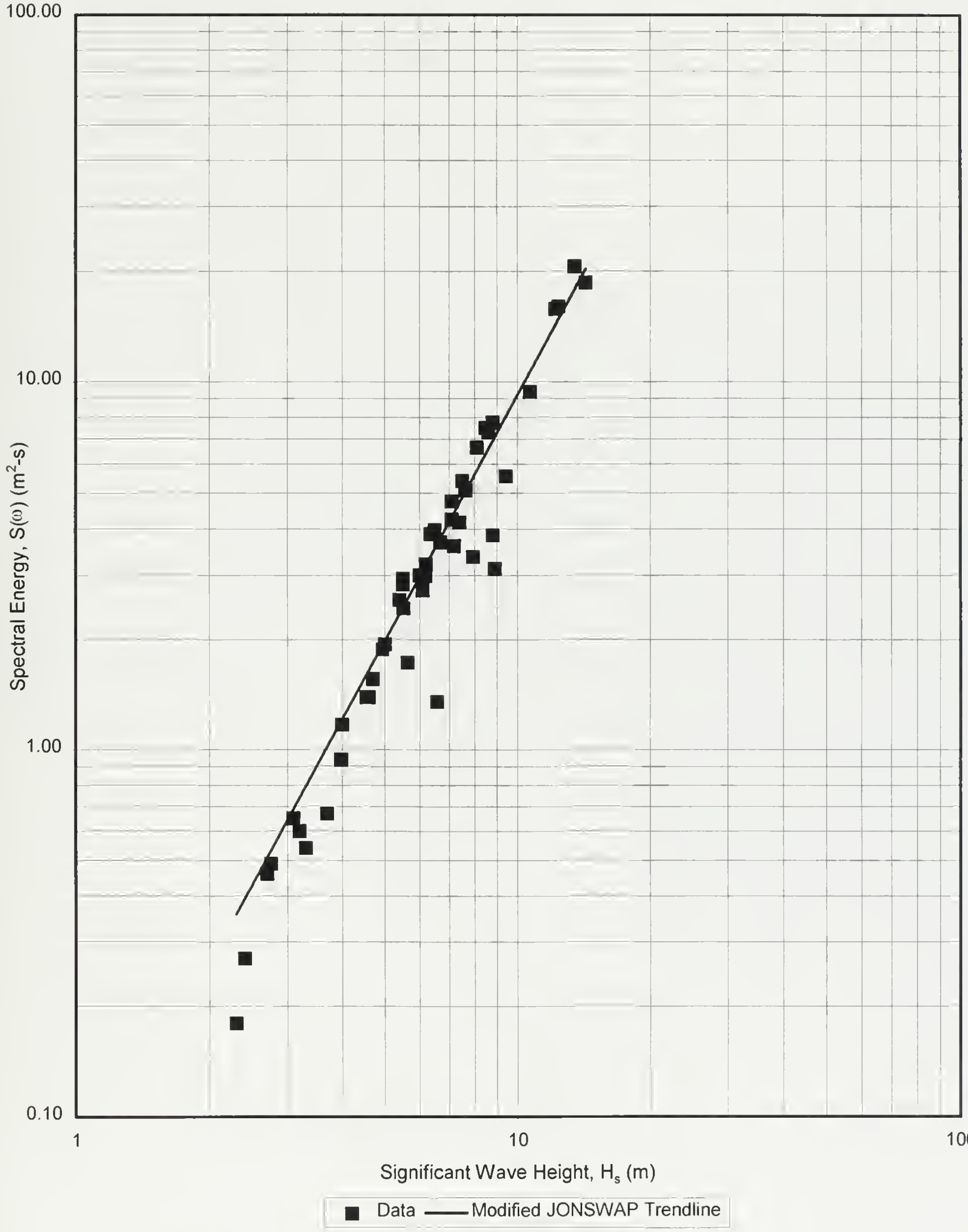


Figure 13 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.35

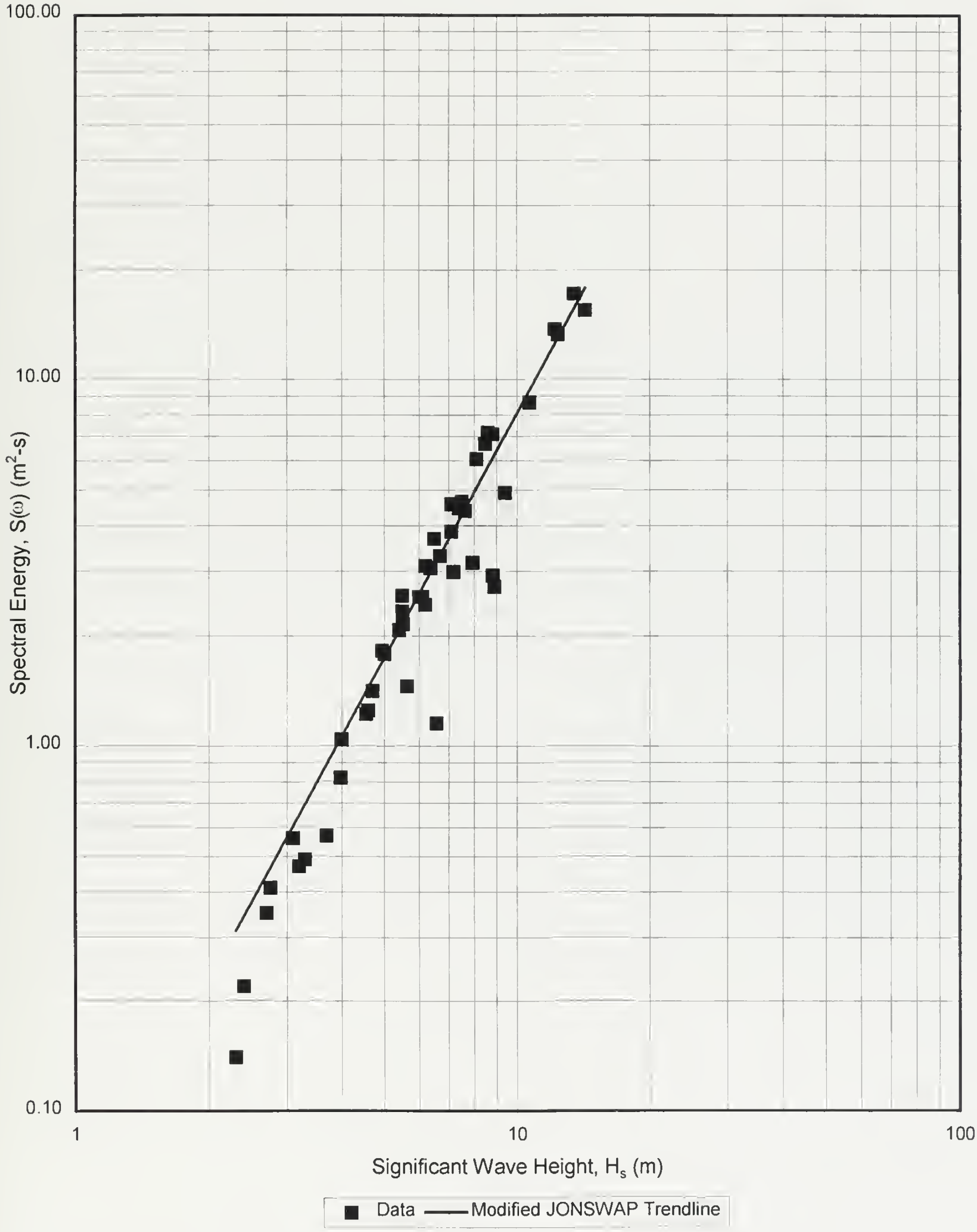
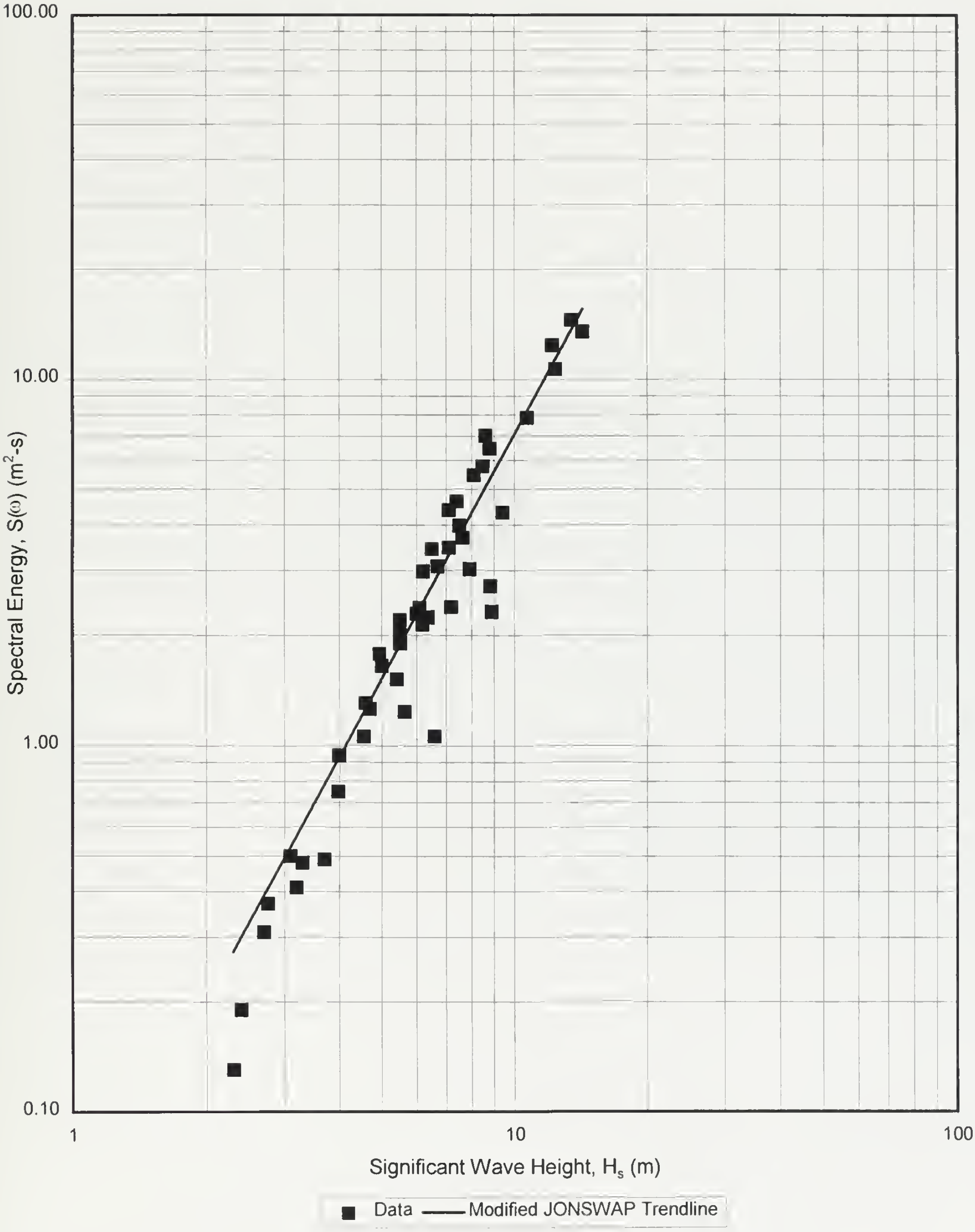


Figure 14 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.40



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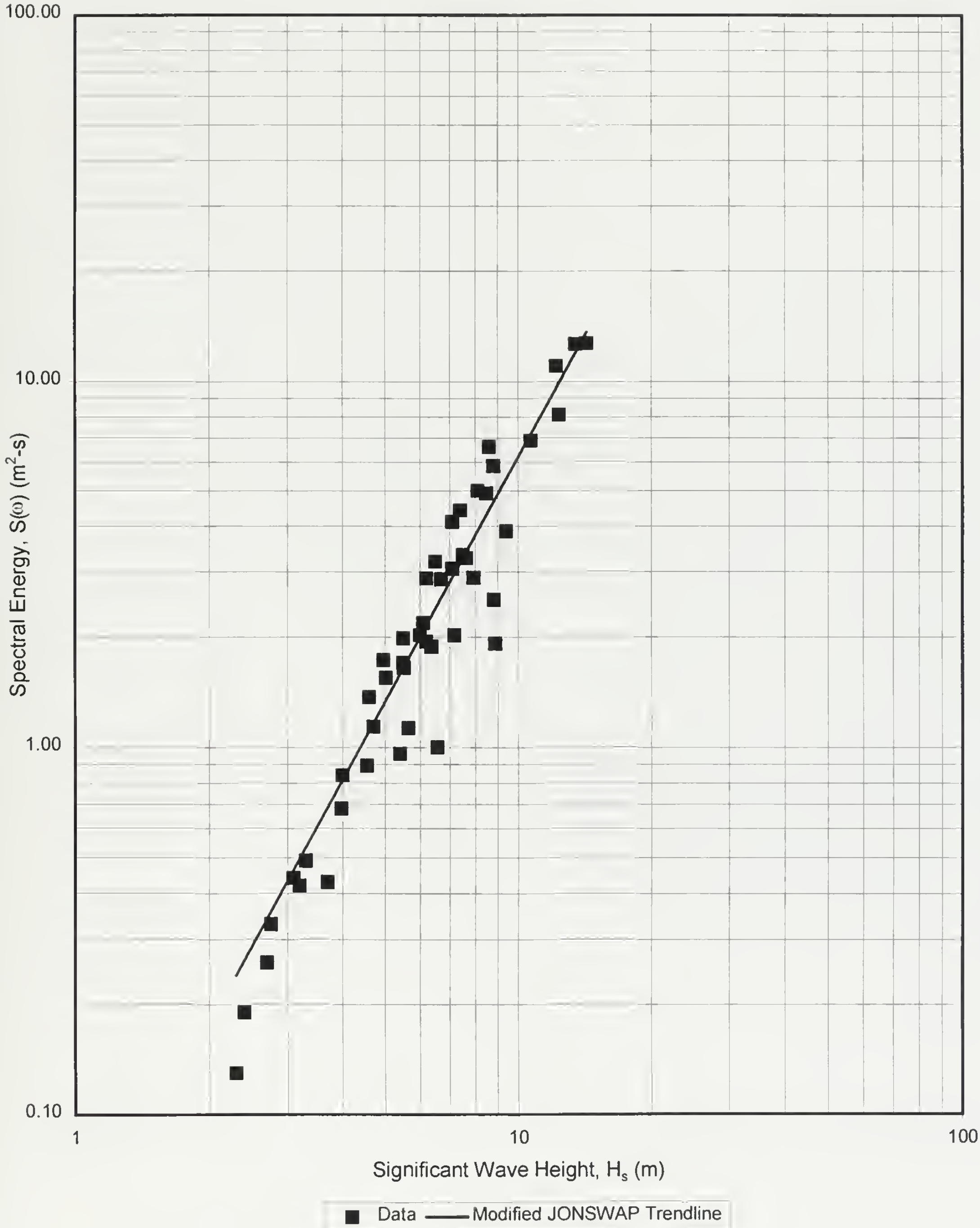


Figure 16 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.50

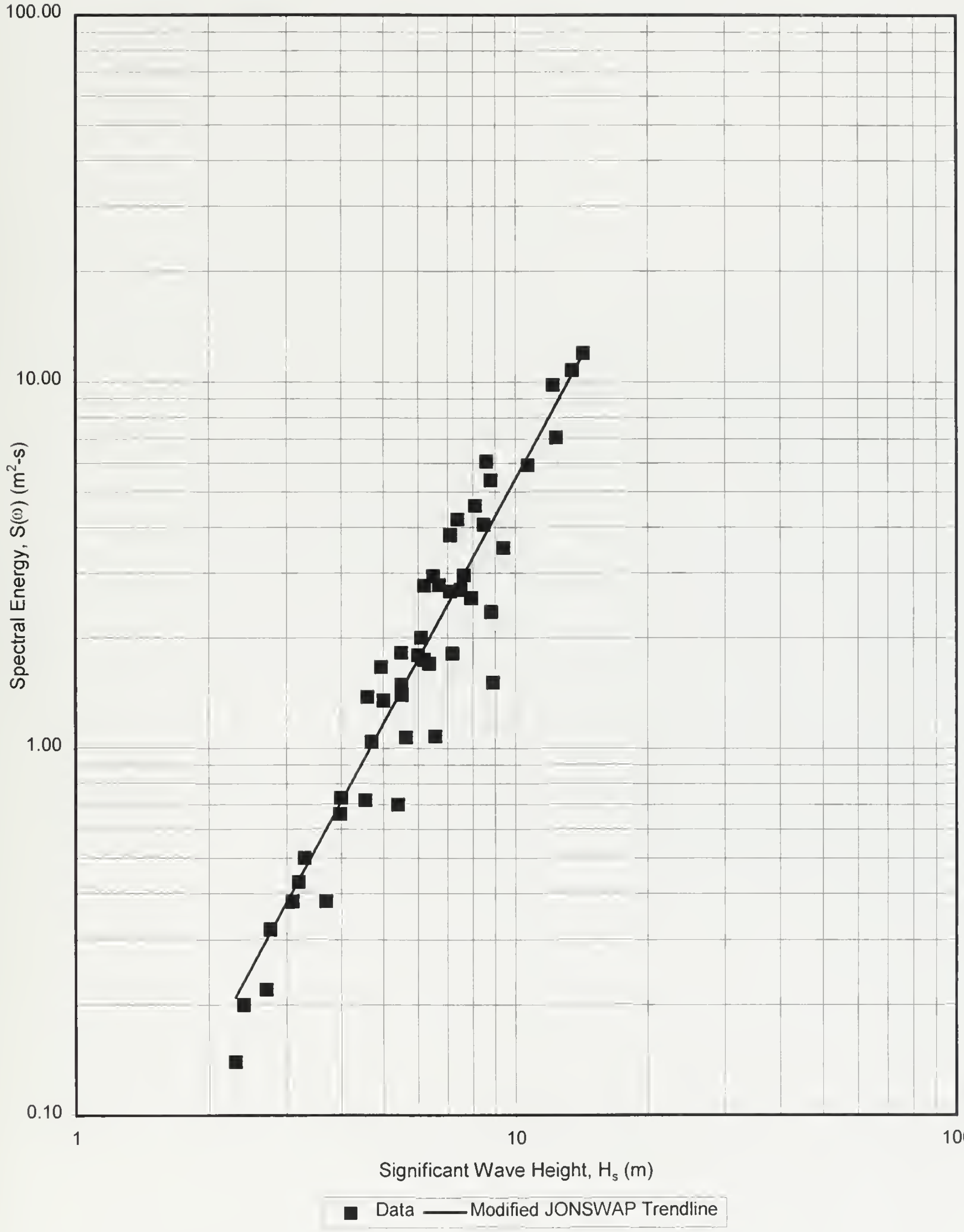


Figure 17 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.55

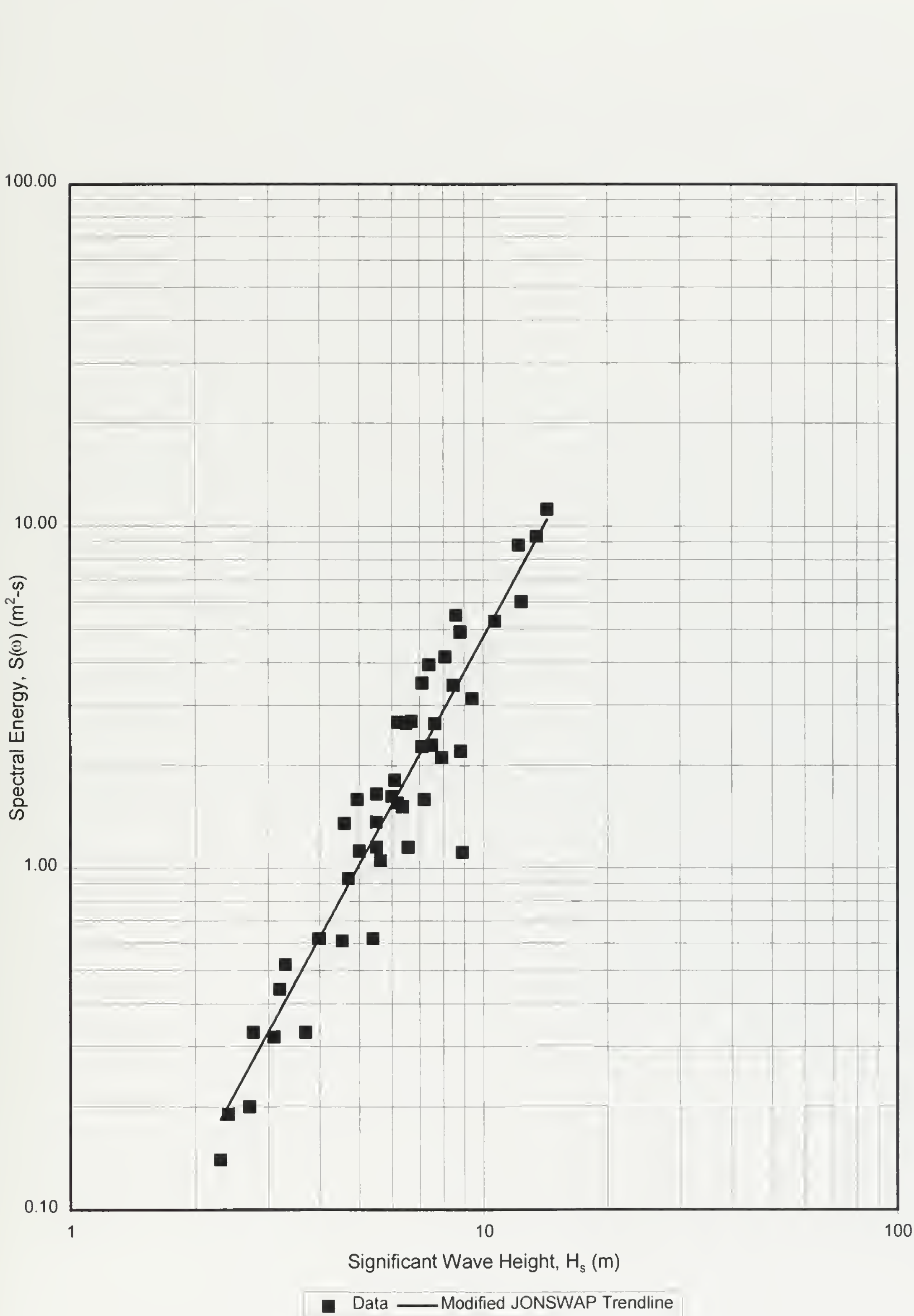


Figure 18 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.60

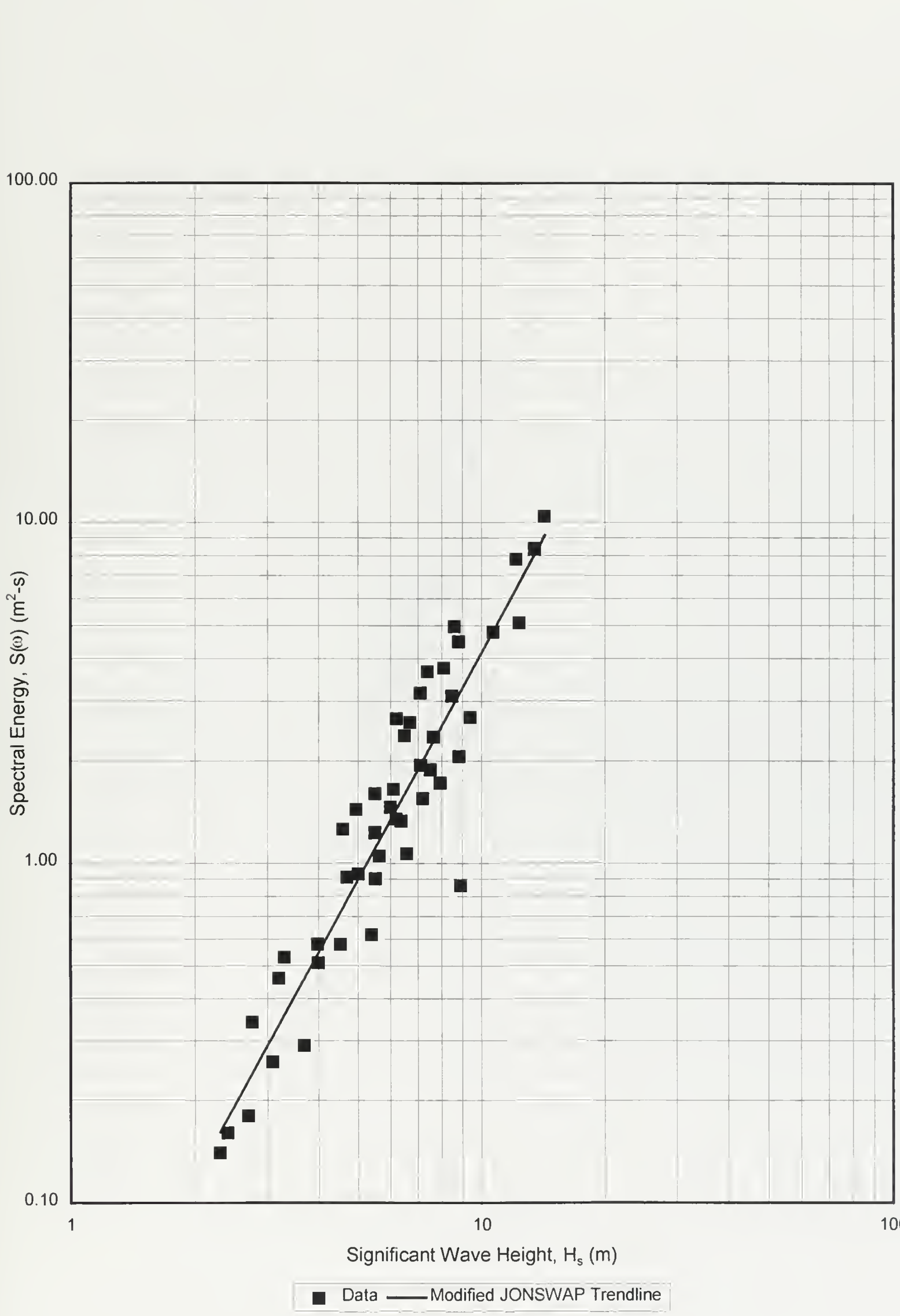
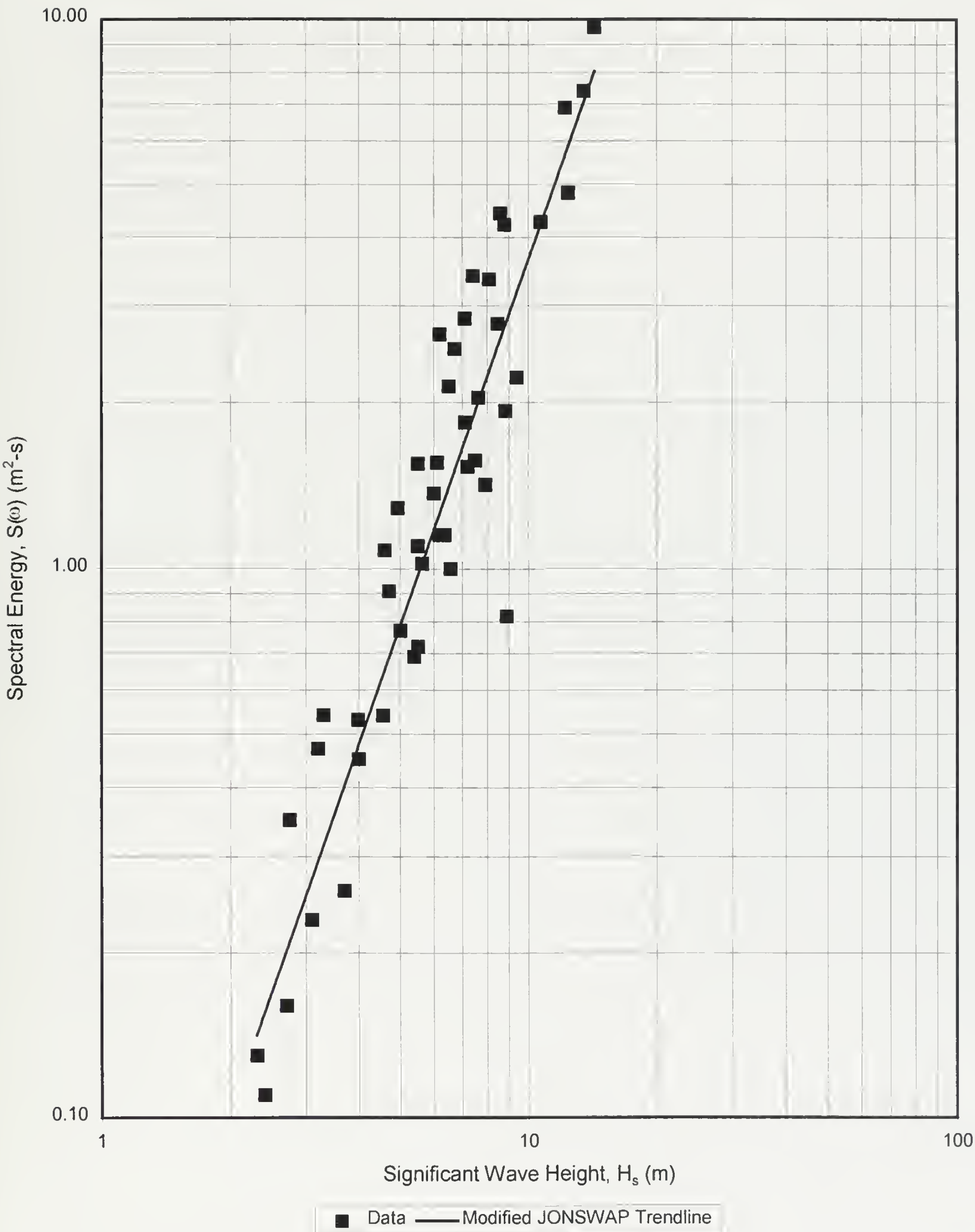


Figure 19 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.65



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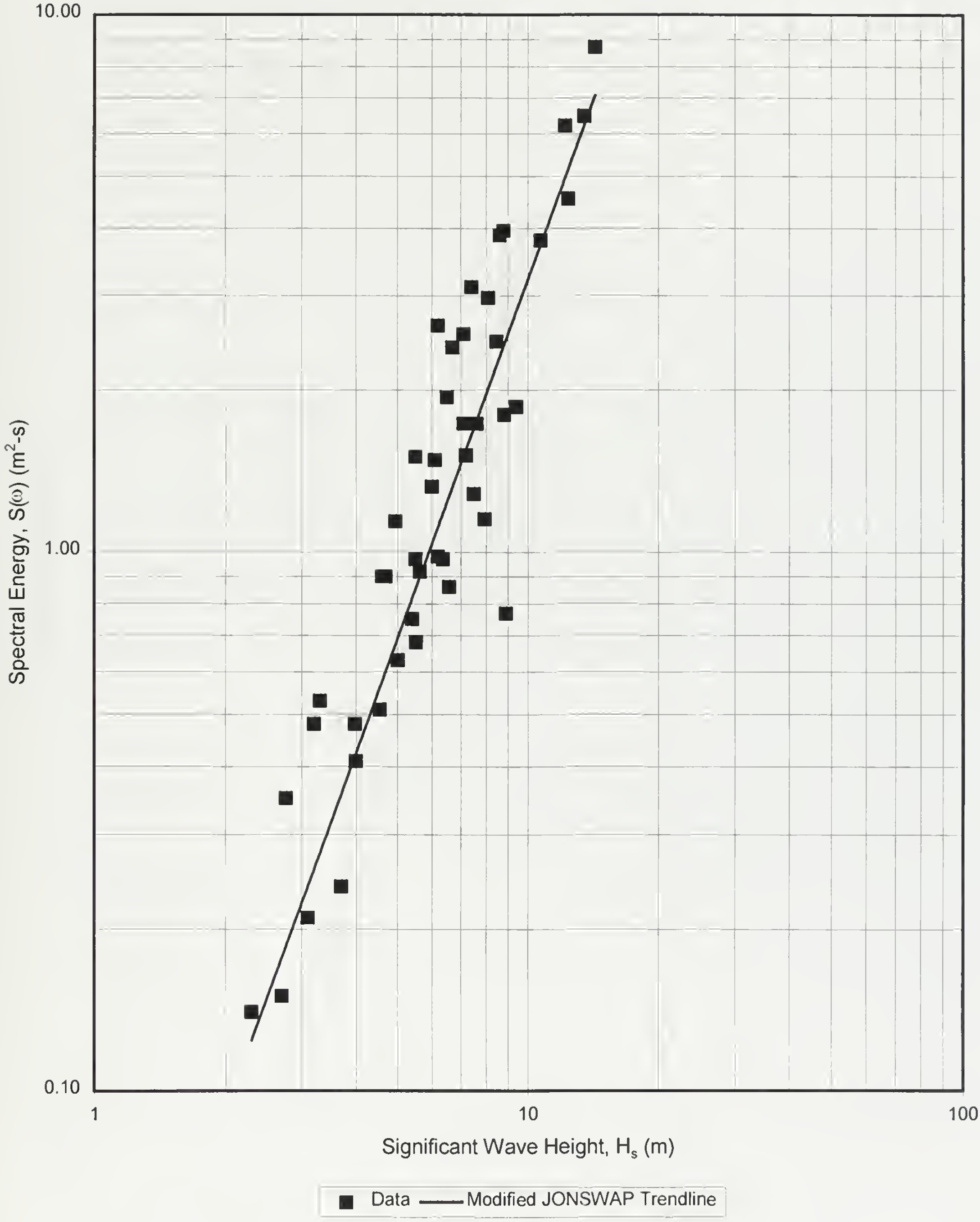

Figure 21 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.75

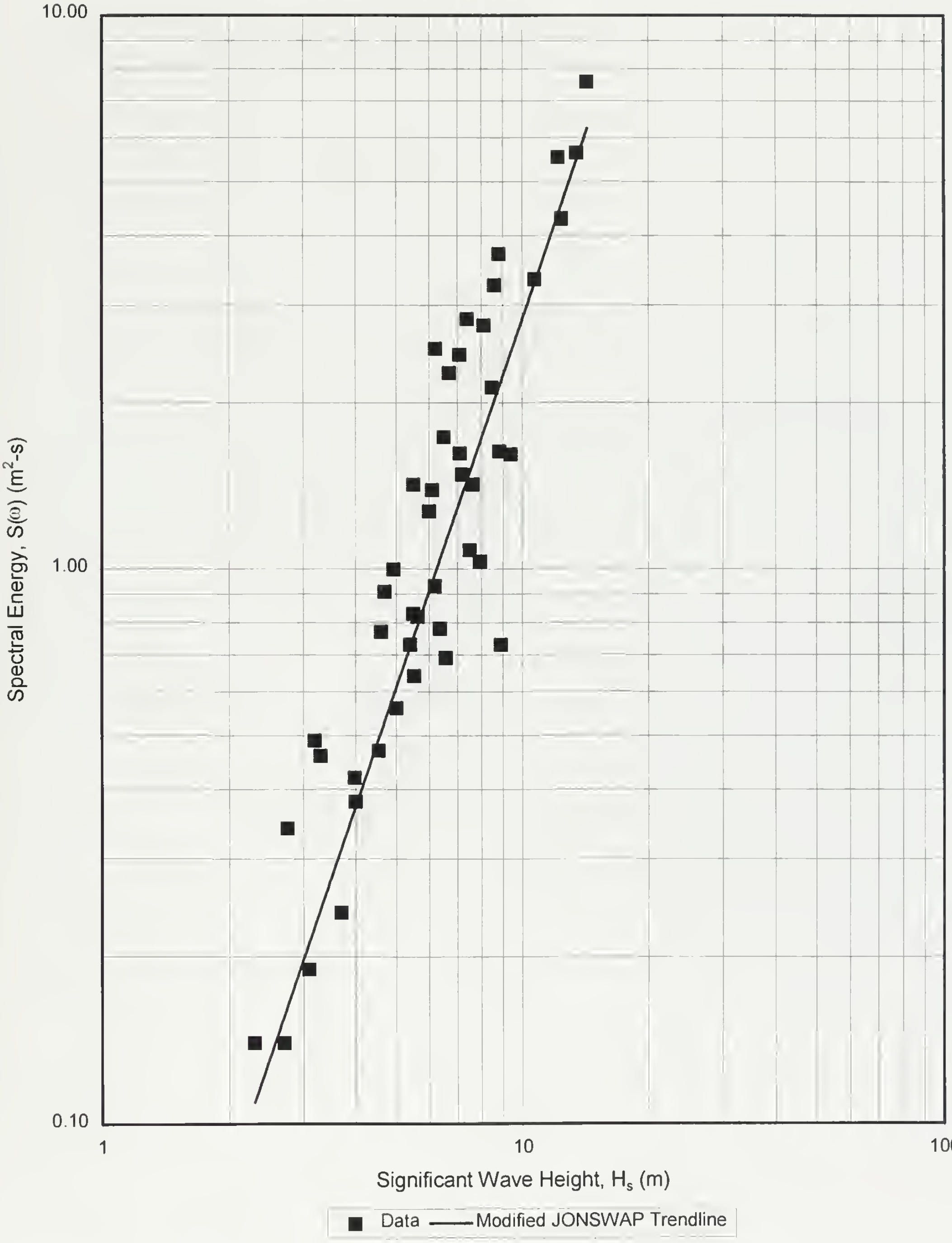

Figure 22 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.80

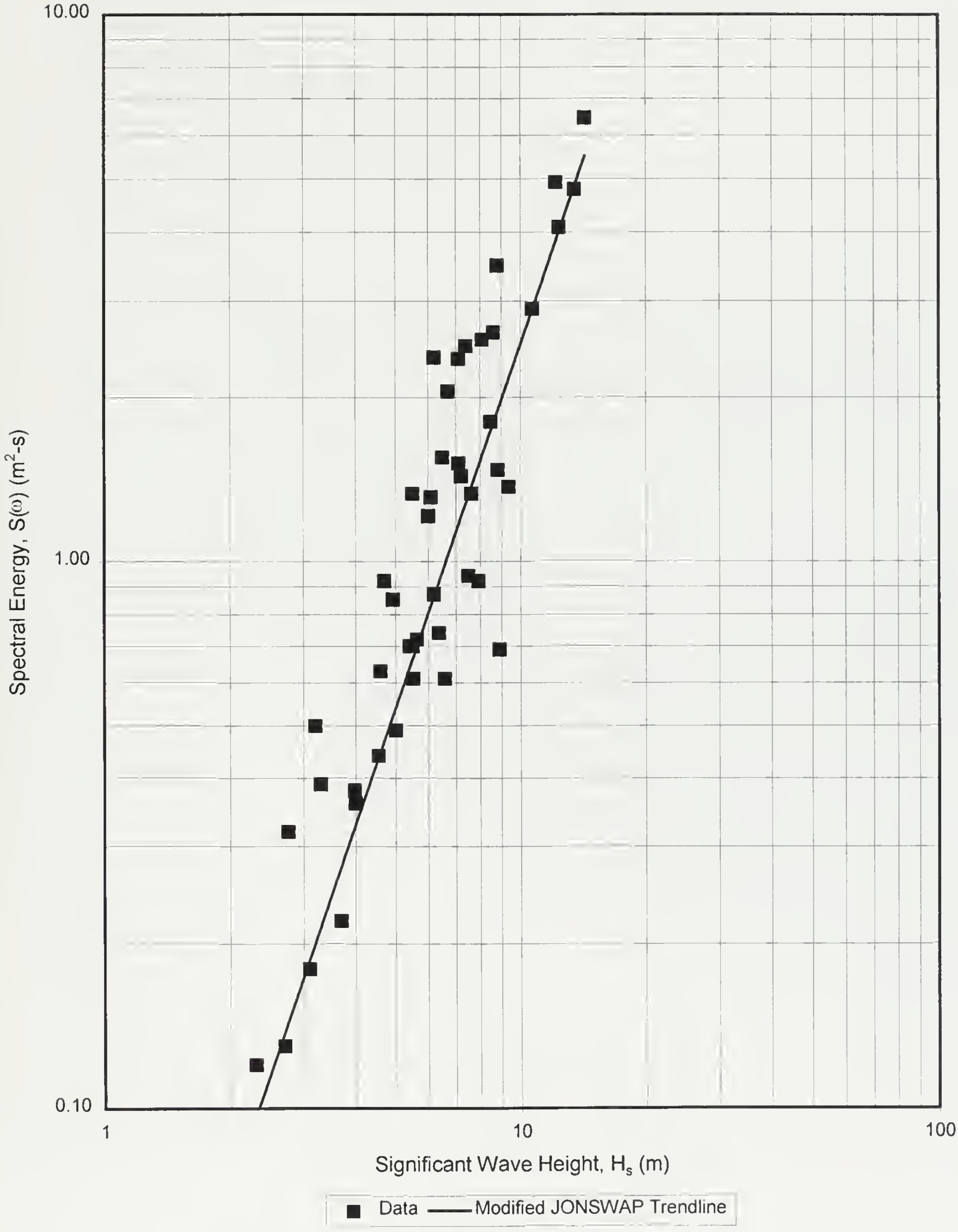

Figure 23 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.85

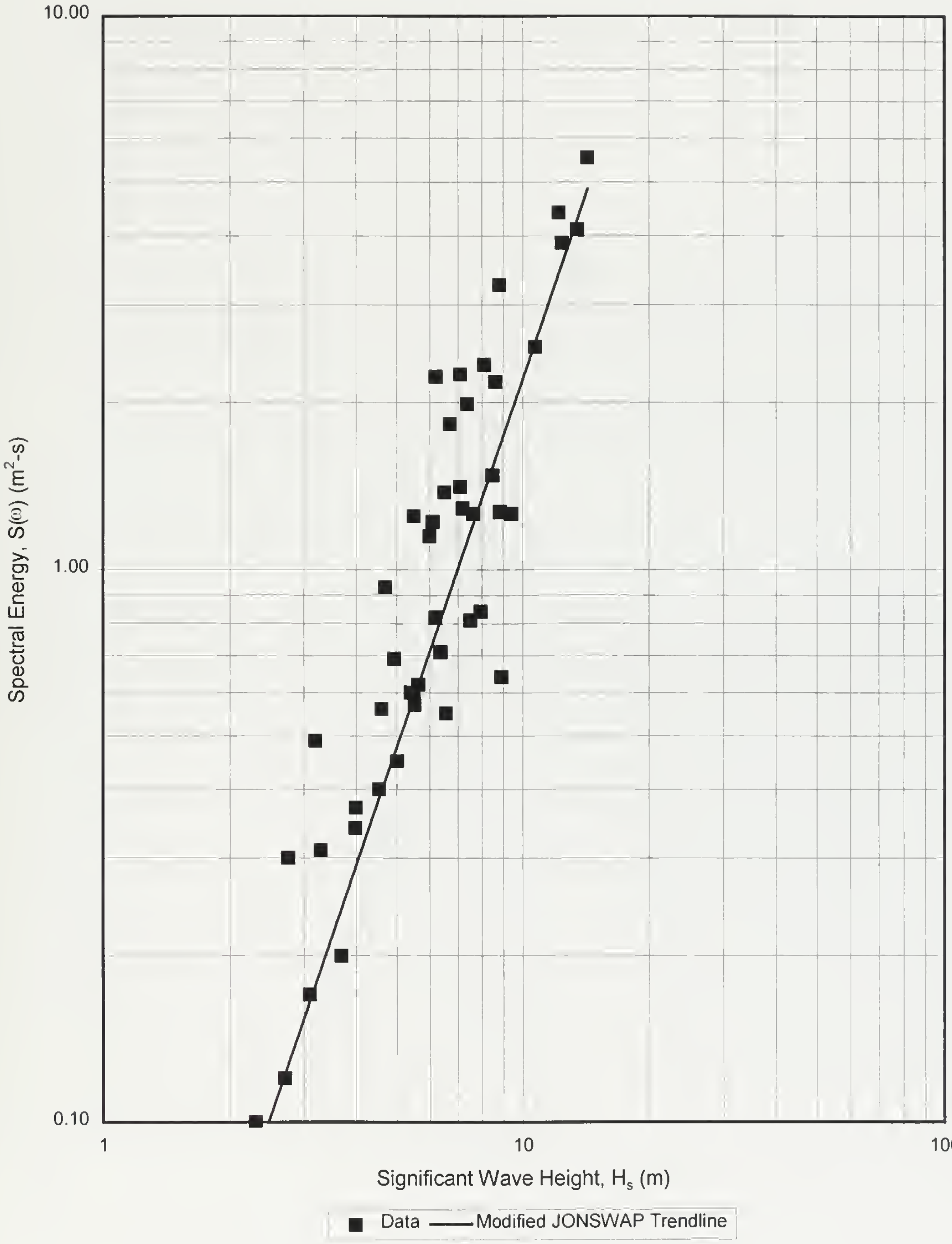

Figure 24 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.90

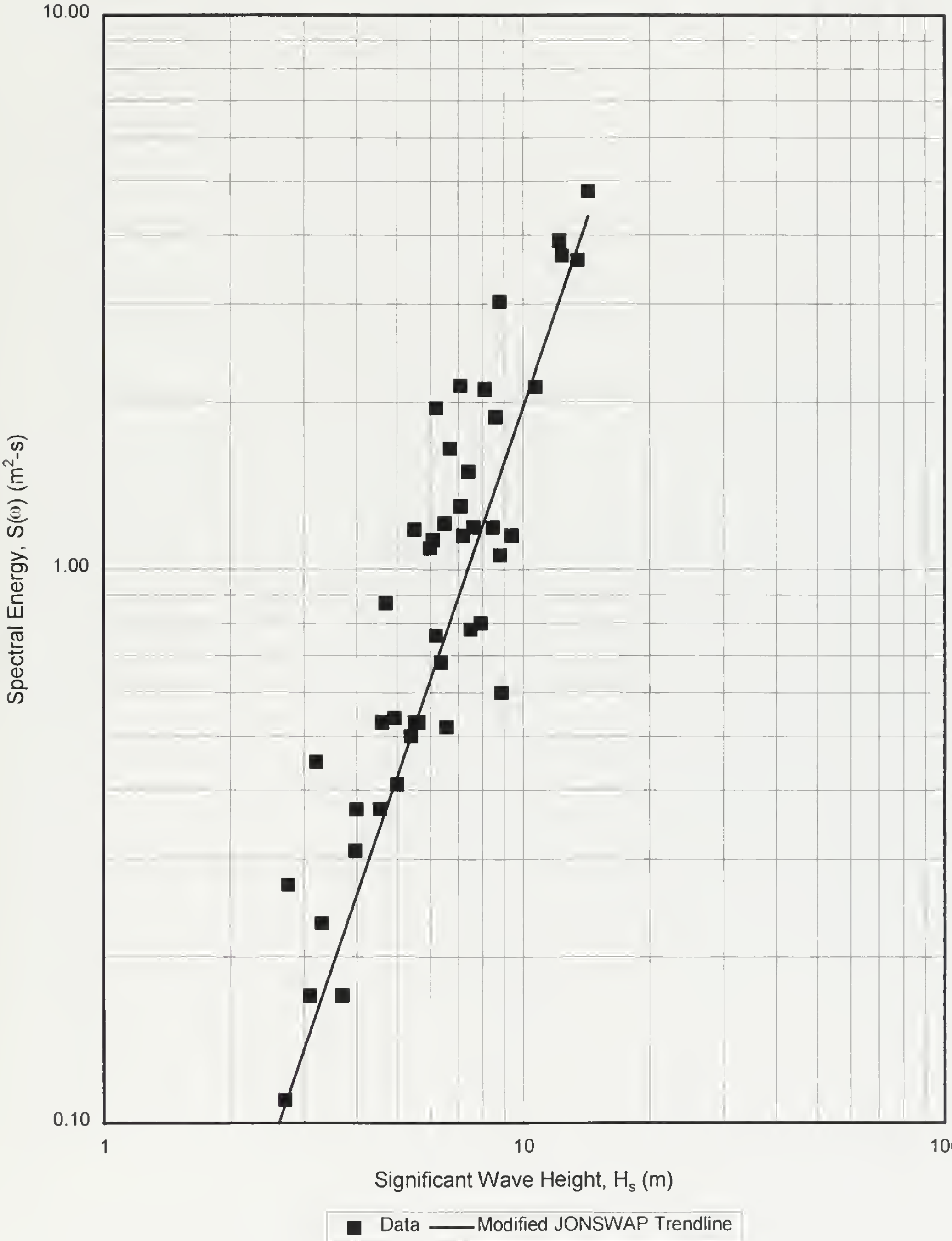

Figure 25 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=1.95

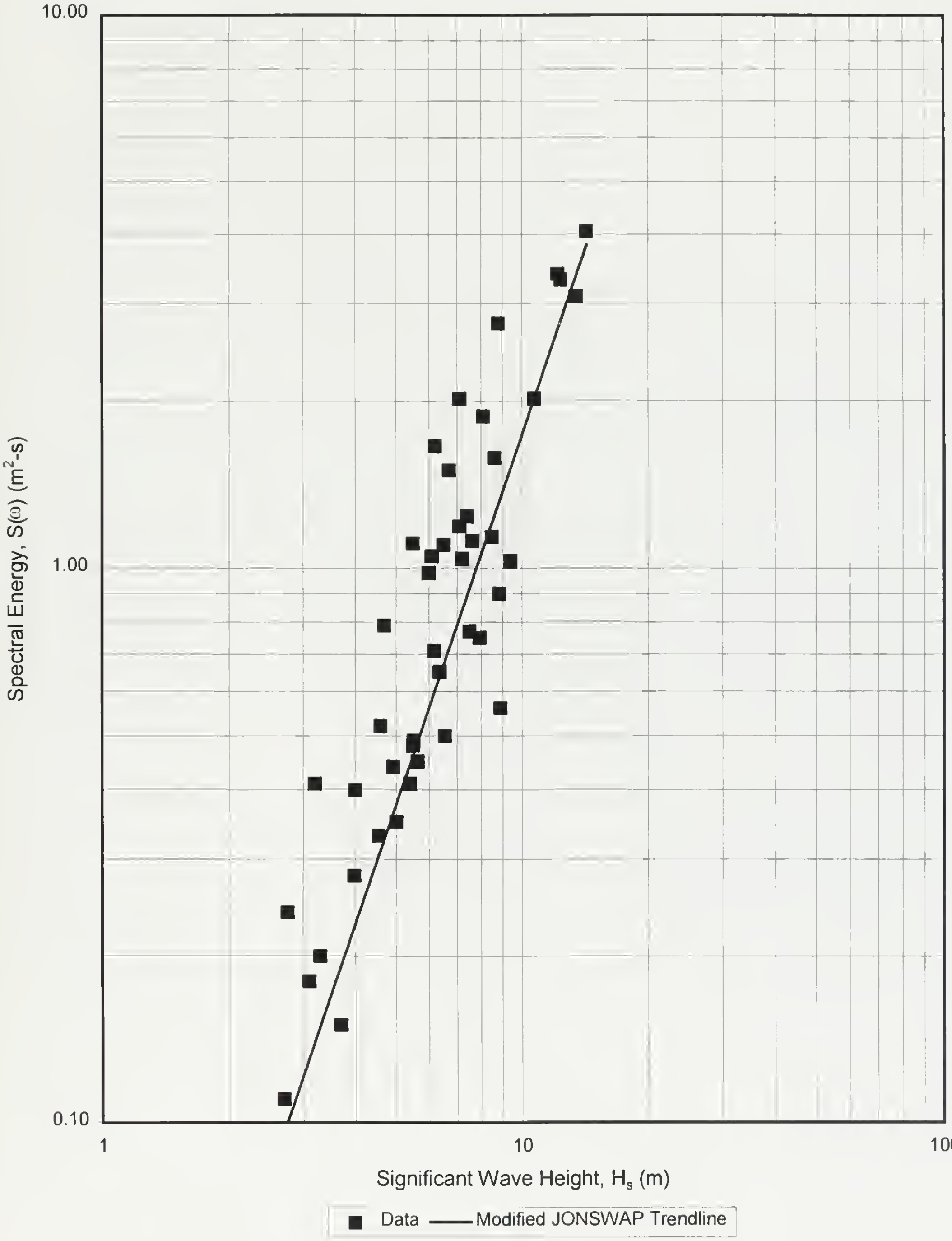

Figure 26 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=2.00

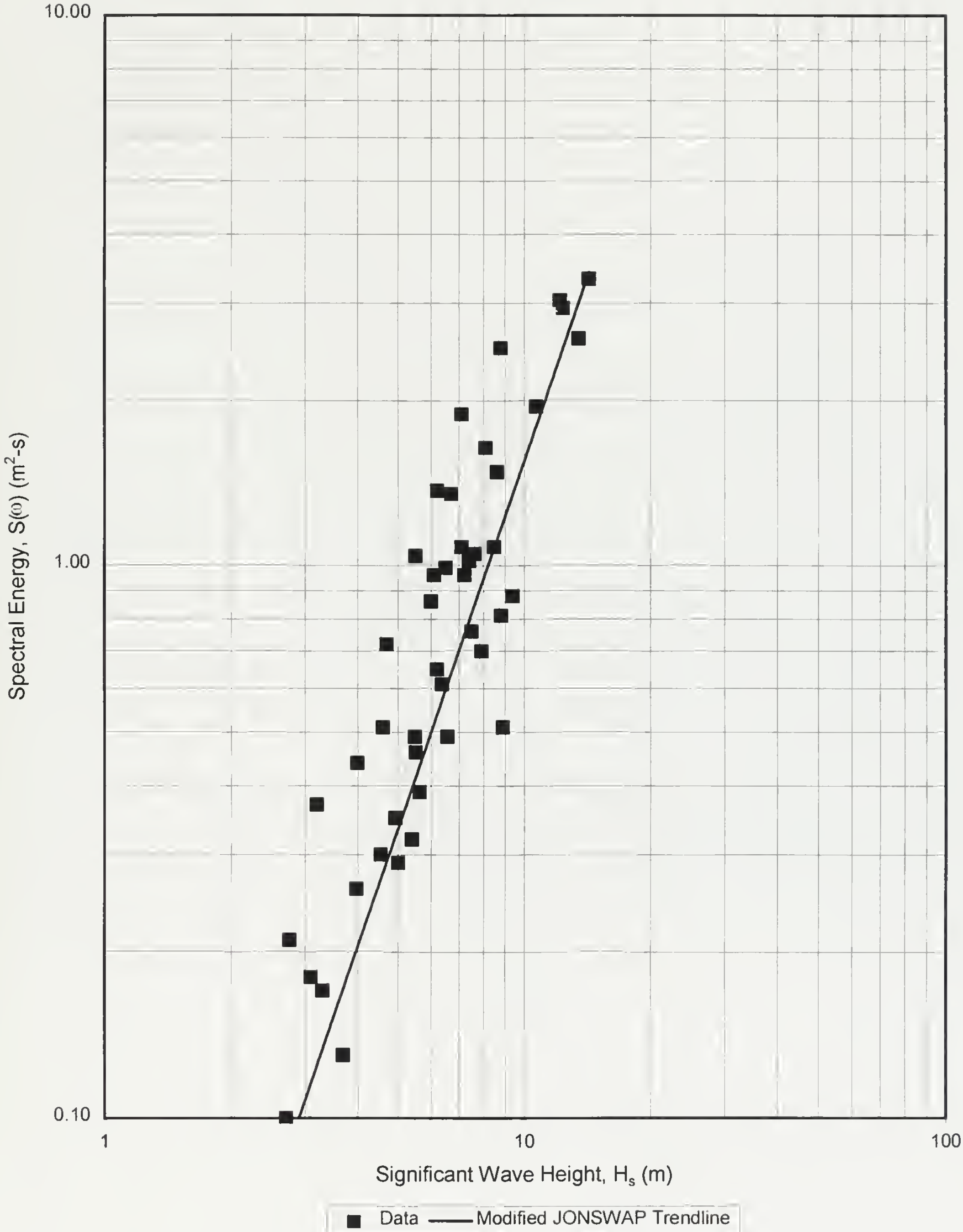

Figure 27 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=2.05

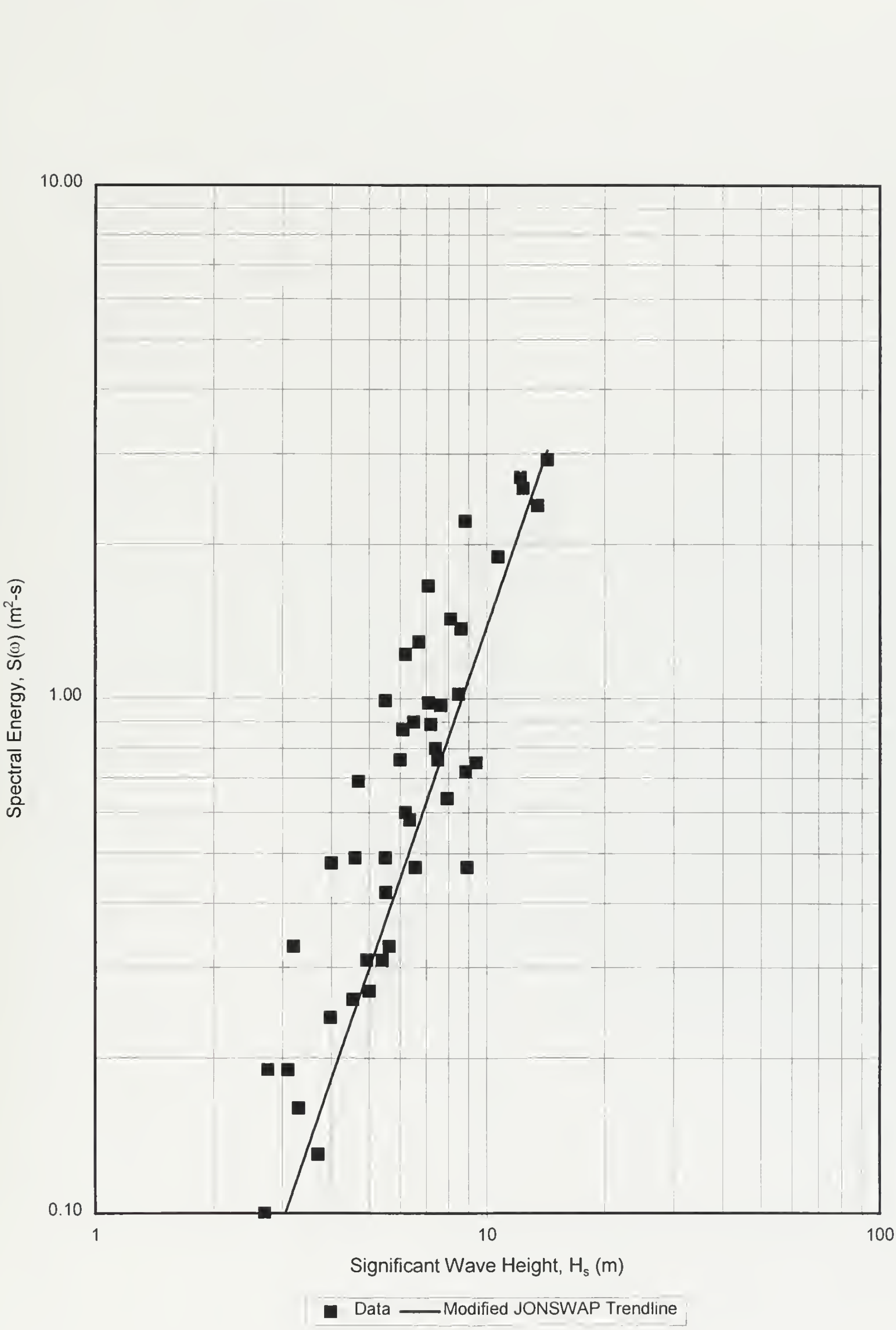

Figure 28 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=2.10

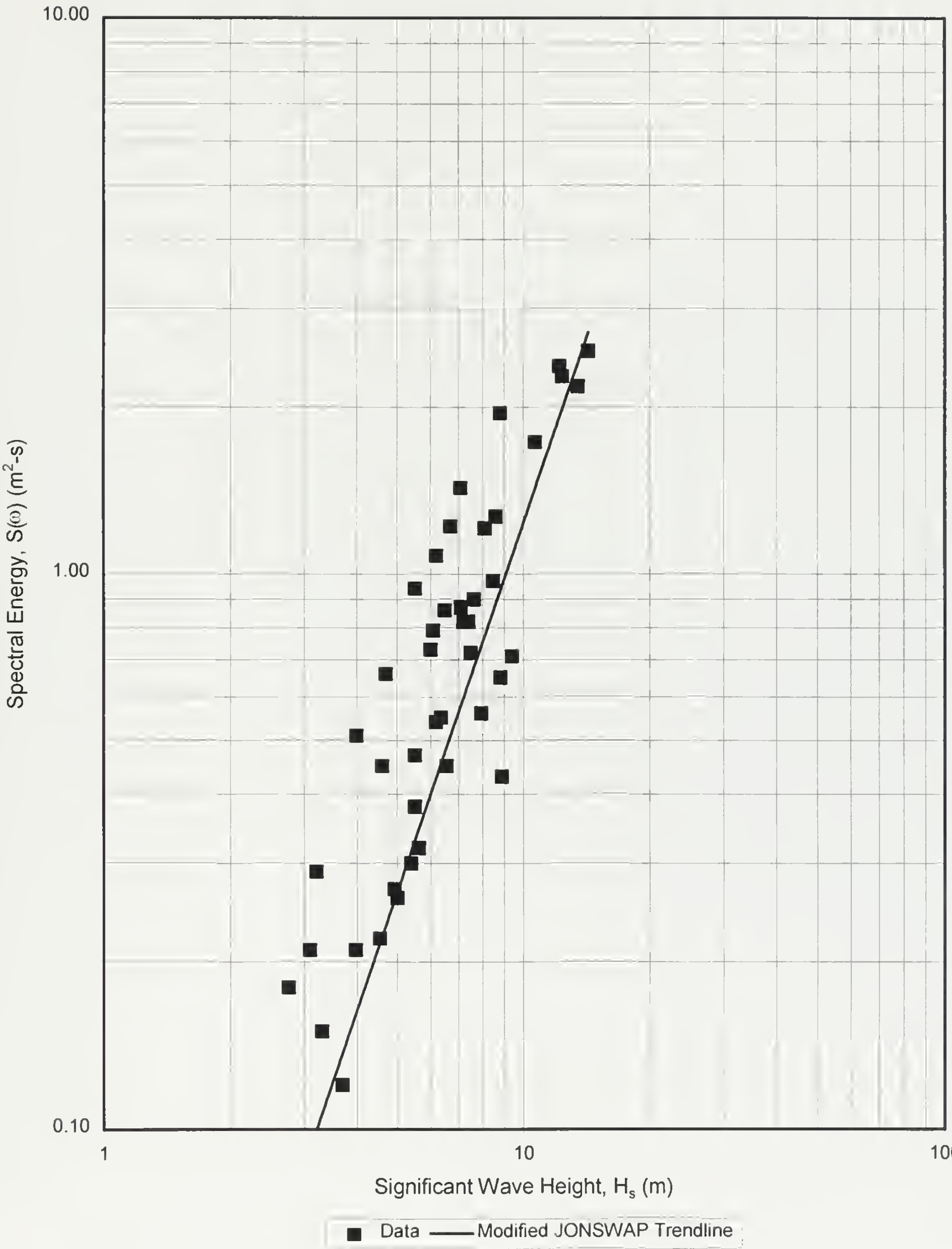

Figure 29 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=2.15

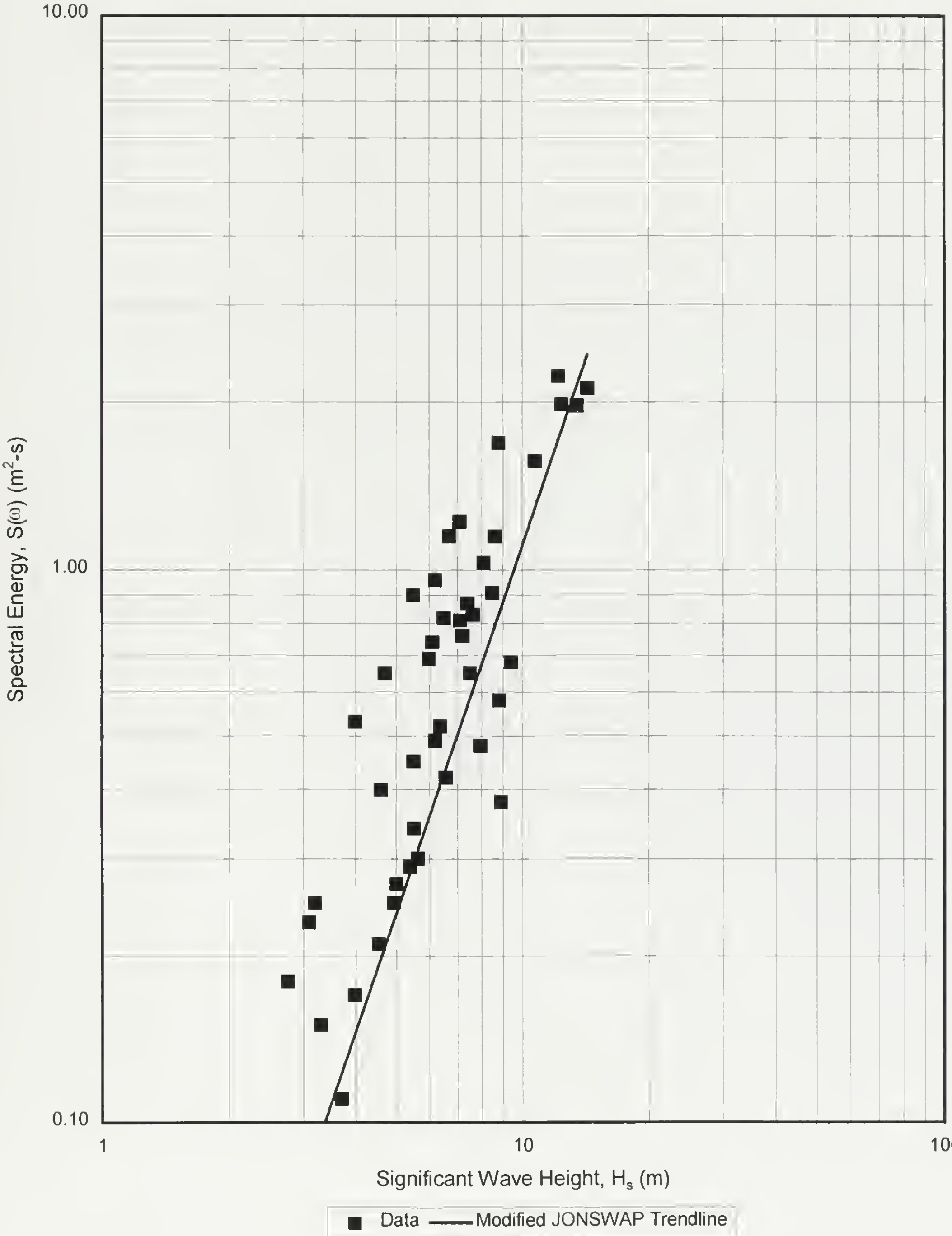

Figure 30 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=2.20

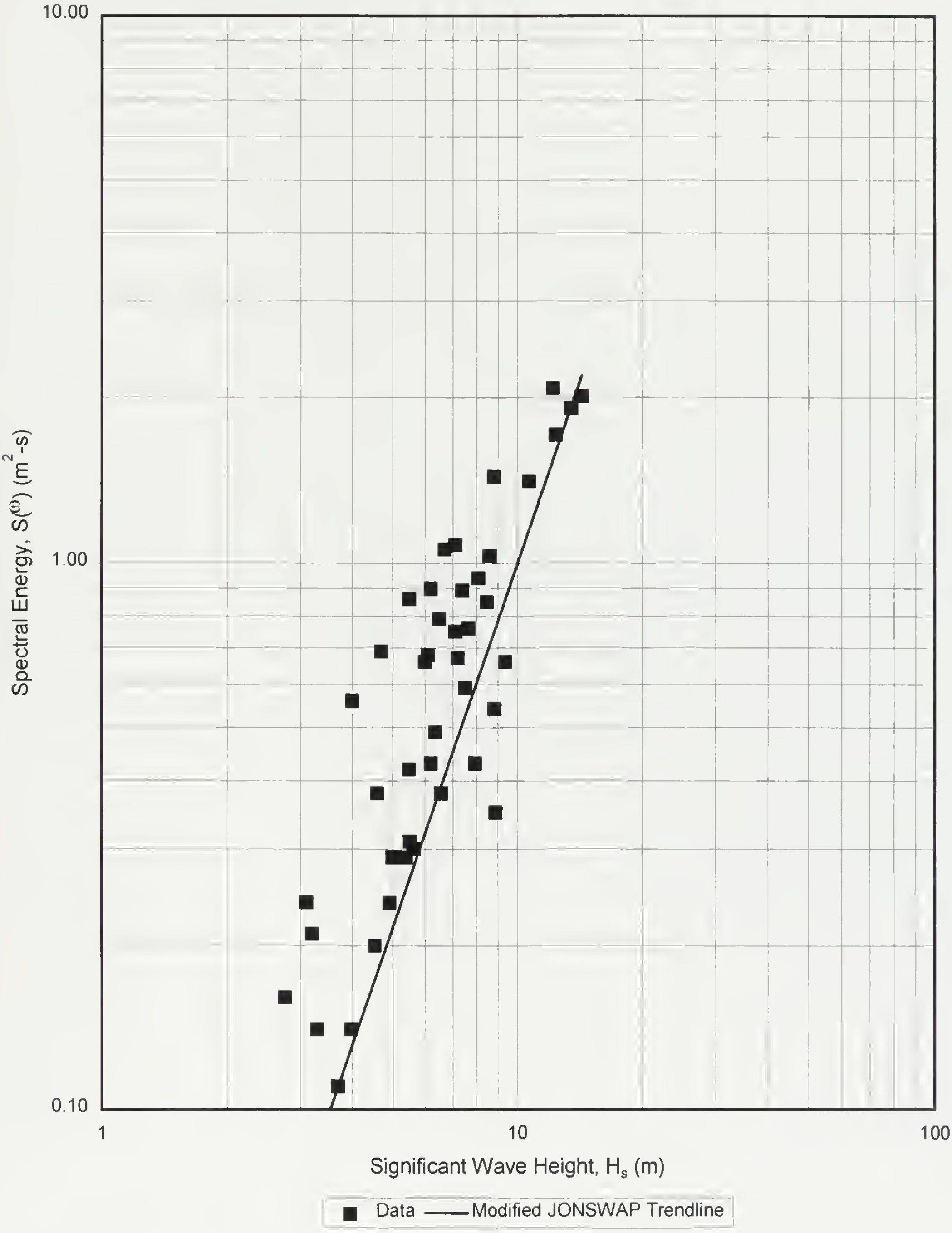

Figure 31 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=2.25

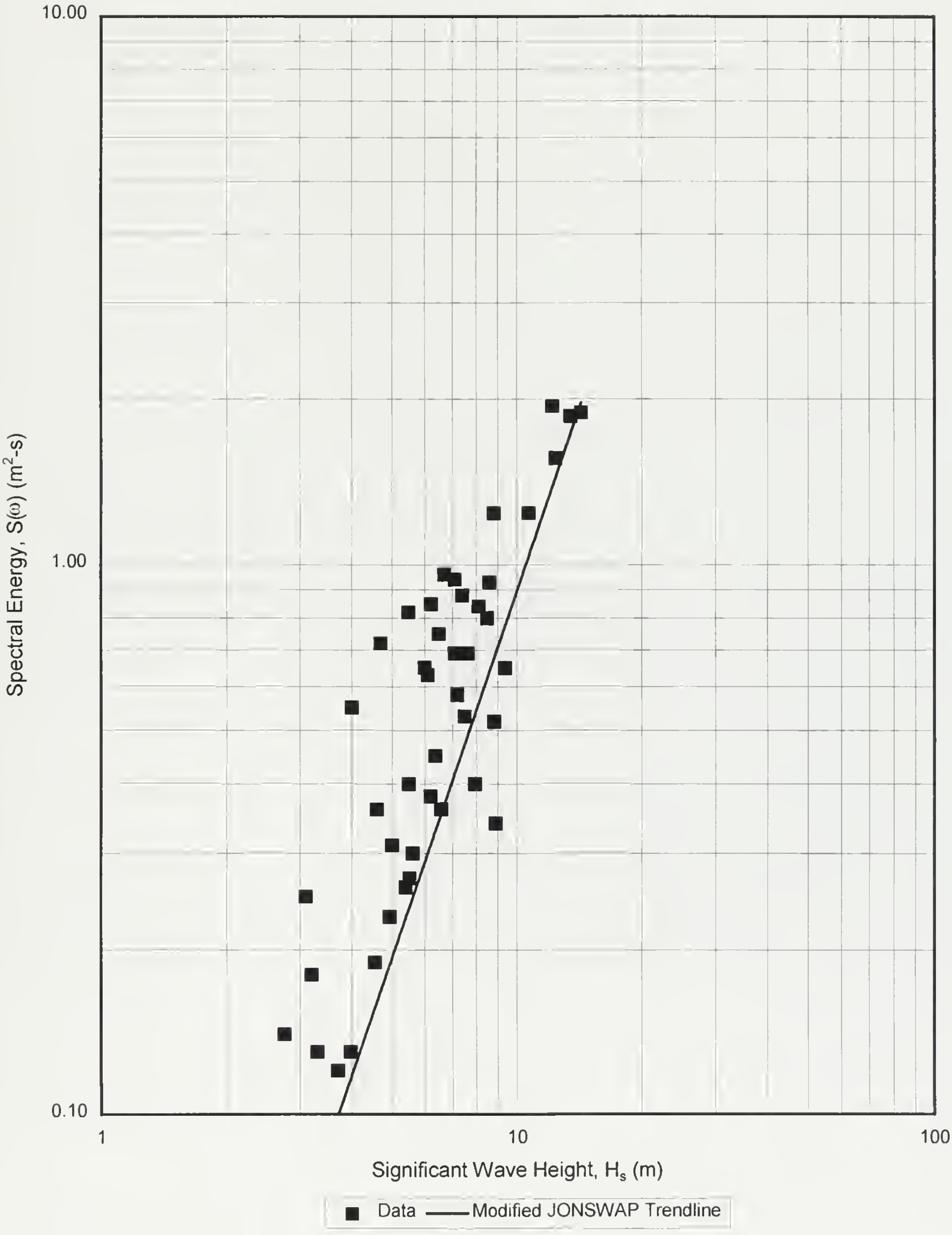

Figure 32 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=2.30

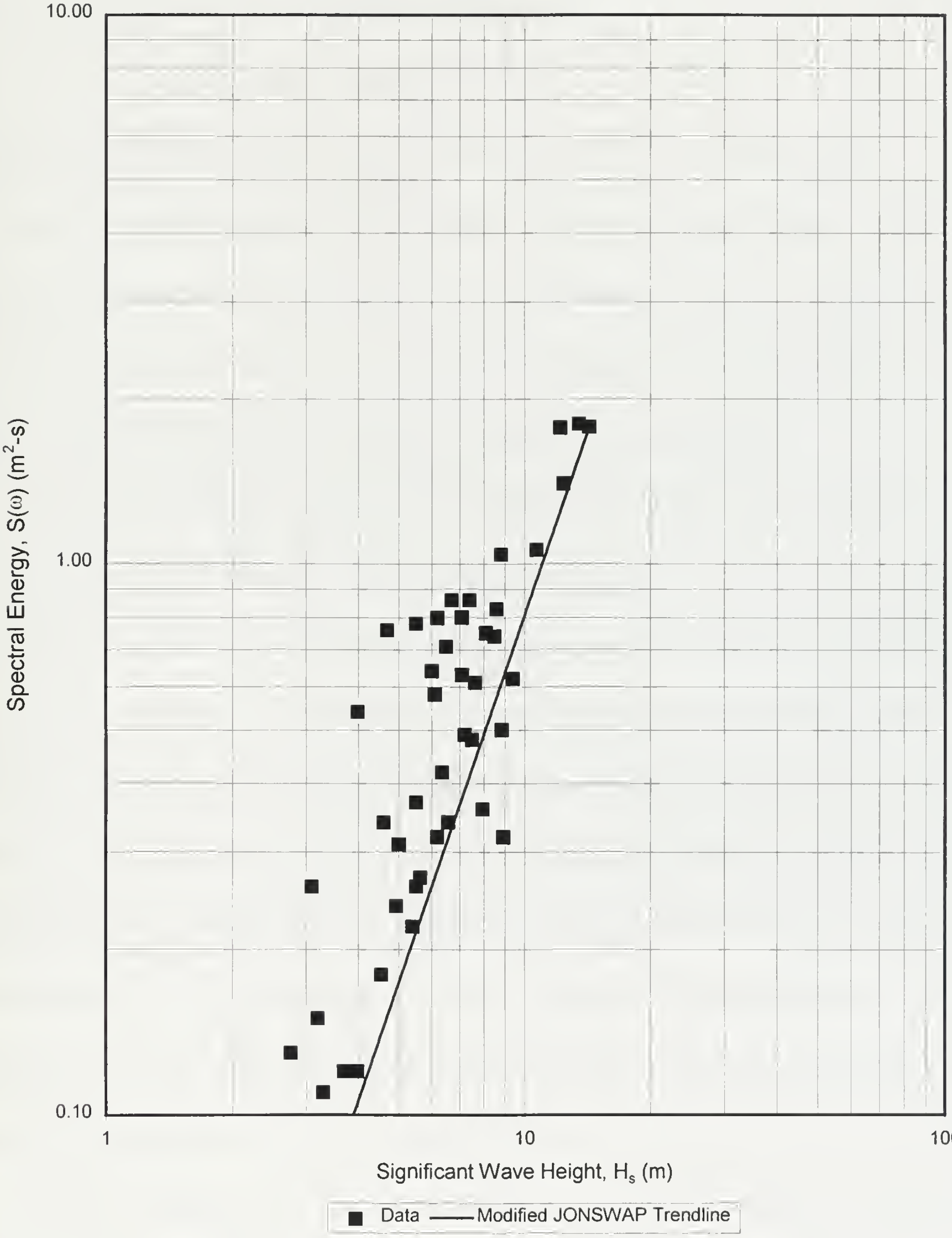

Figure 33 Modified JONSWAP spectrum versus significant wave height for ω/ω_m=2.35

The Pierson-Moskowitz and the two parameter spectra have been included to show how well they represent hurricane generated wave spectra.

The two parameter and Modified JONSWAP both require a given modal frequency and significant wave height. For the plots in Figure 34 through 44 the corresponding modal frequency from the data presented in the figure is used. For this reason the two parameter and Modified JONSWAP have the same modal frequency as the data. On the other hand, the Pierson-Moskowitz formula requires only significant wave height. Modal frequency is then a function of significant wave height.

Wave spectra data for hurricane Belle (Figures 34 through 36) and Gloria (Figures 37 and 38) are similar in that both storms grew after several days of moderate sea severity. For Belle at a significant wave height of 3.2m (Figure 34), a second peak can be seen at 1 rad/sec. This represents a significant preexisting sea severity before the hurricane. As the hurricane grows to a significant wave height of 6.1m (Figure 35) and then to 7.1m (Figure 36) this second peak becomes small in comparison to the energy contained at the modal frequency. As Gloria grows from a significant wave height of 6.0m (Figure 37) to 8.1m (Figure 38) a similar second peak is present and then disappears because of energy associated with the hurricane dominates the energy pre-existing in the spectrum.

Gloria at a significant wave height of 8.1m shows a good comparison between the Pierson-Moskowitz, the two parameter and the Modified JONSWAP. Before Gloria passed the NOAA buoy, a continuos wind of 7-11 m/s blew for 10 days so the sea had a sufficient amount of time to be fully developed (Pierson et al., 1958). Consequently, at

this stage in the growth of Gloria, the Pierson-Moskowitz formula predicts the same modal frequency as the data, but slightly under predicts the shape of the spectra and maximum energy. The two parameter formula gives similar results. Belle and Gloria both grow significantly at their modal frequencies, which are concentrated in the lower end of the frequency domain.

The wave spectral growth of Eloise from a significant wave height of 5.6m (Figure 39) to 8.8m (Figure 40) shows a similar trend as that of Fredrick from 4.5m (Figure 41) to 5.5m (Figure 42) and then to 8.5m (Figure 43). They exhibit growth predominantly at the modal frequency, again located at lower frequencies. In all stages of growth for all storms, the data shows spectra with a sharp peak at the modal frequency which is represented well by the Modified JONSWAP formula. This peak becomes more pronounced at higher significant wave heights which can be seen in Kate at a significant wave height of 10.7m (Figure 44).

Plotting individual spectra shows the obvious advantage of using the Modified JONSWAP formula to represent wave spectra for hurricane generated seas, as it represents maximum energy and shape reasonably well at various hurricane intensities. The figures show that the Pierson-Moskowitz and two parameter formulas both under predict maximum values and give an extended shape at the modal frequency. The Pierson-Moskowitz and two parameter formulations do not, in general, represent hurricane generated sea state.

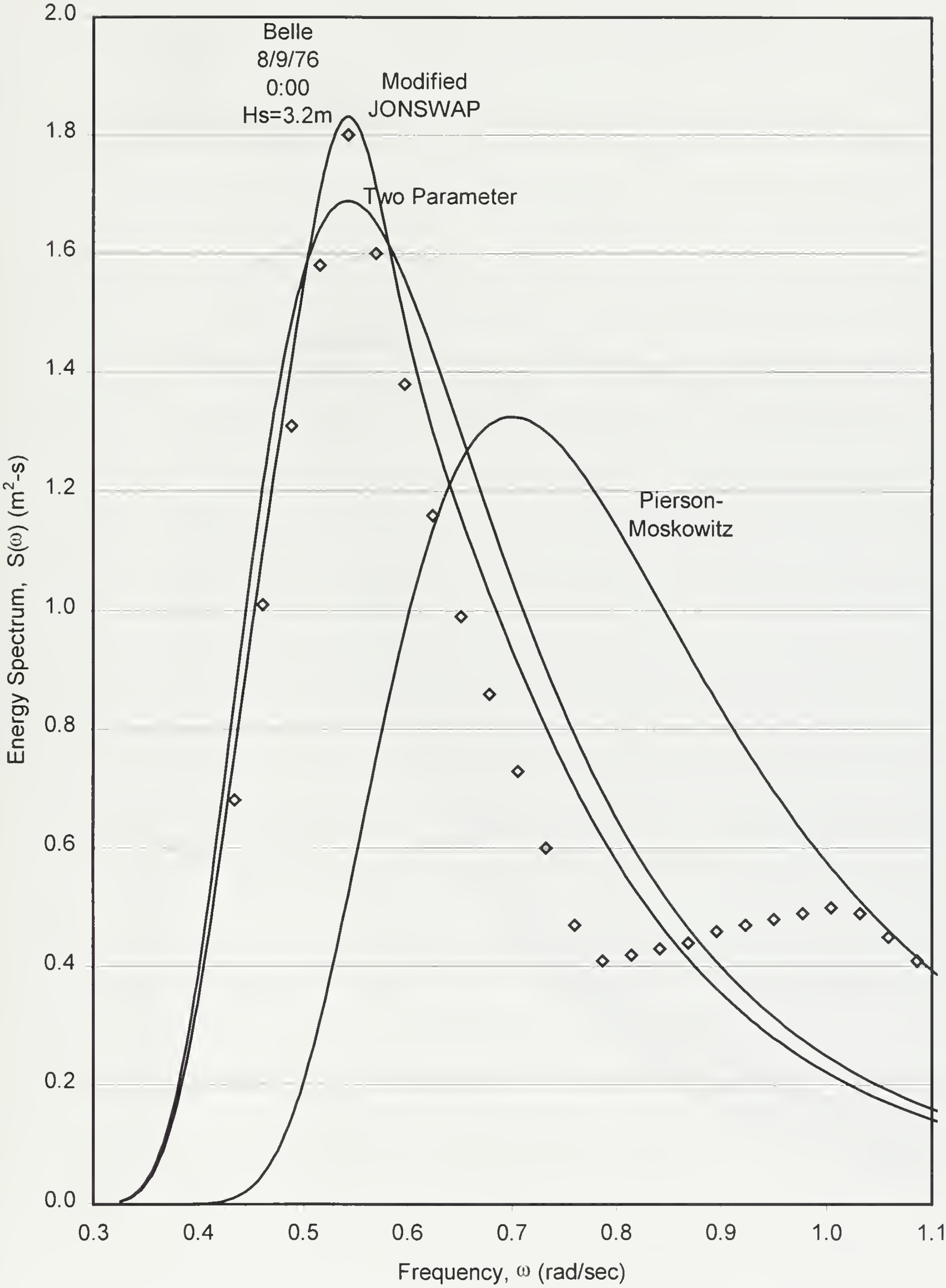

Figure 34 Comparison between Modified JONSWAP and measured spectrum for Hurricane Belle, H_s=3.2 m

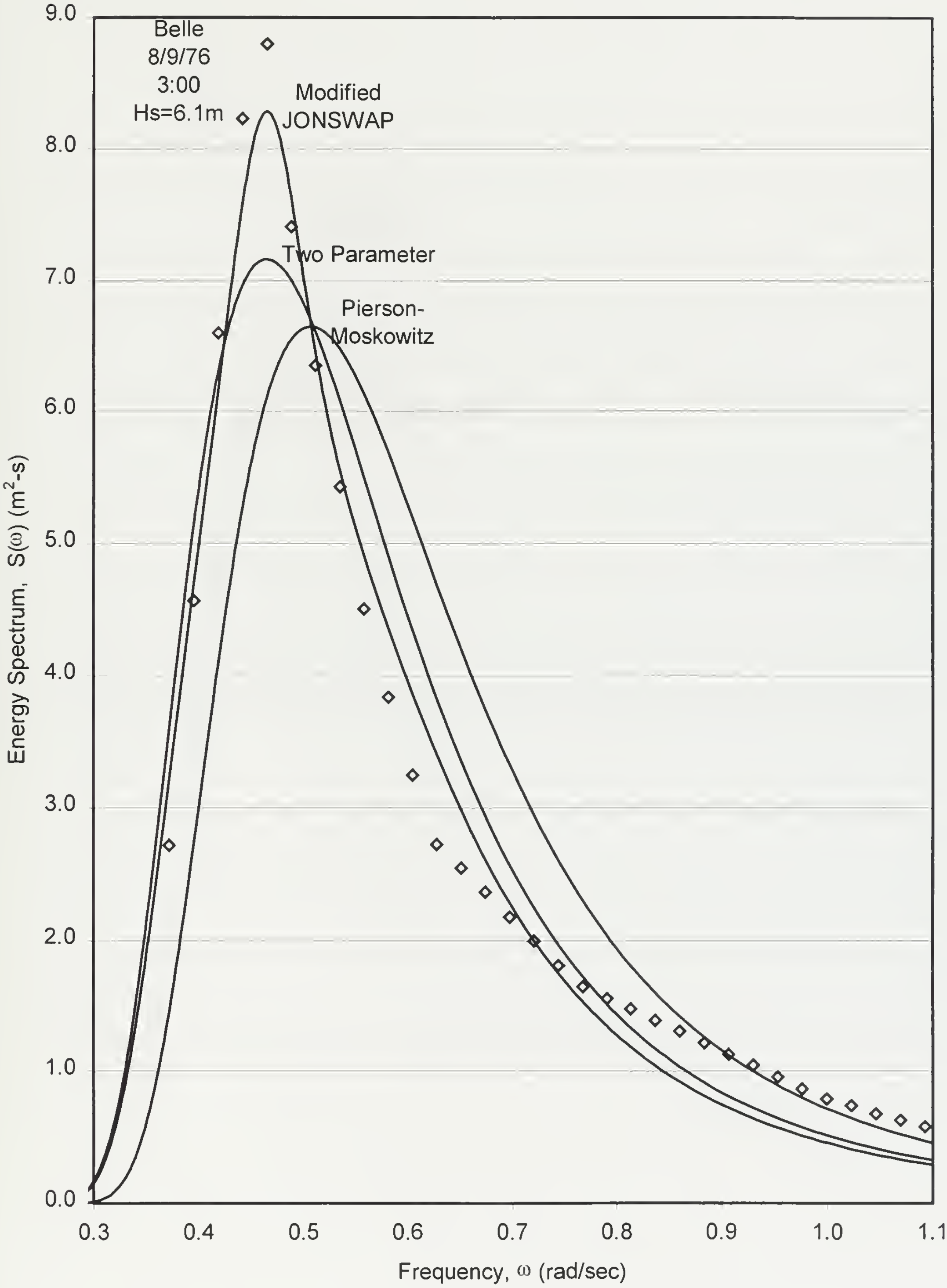

Figure 35 Comparison between Modified JONSWAP and measured spectrum for Hurricane Belle, H_s=6.1 m

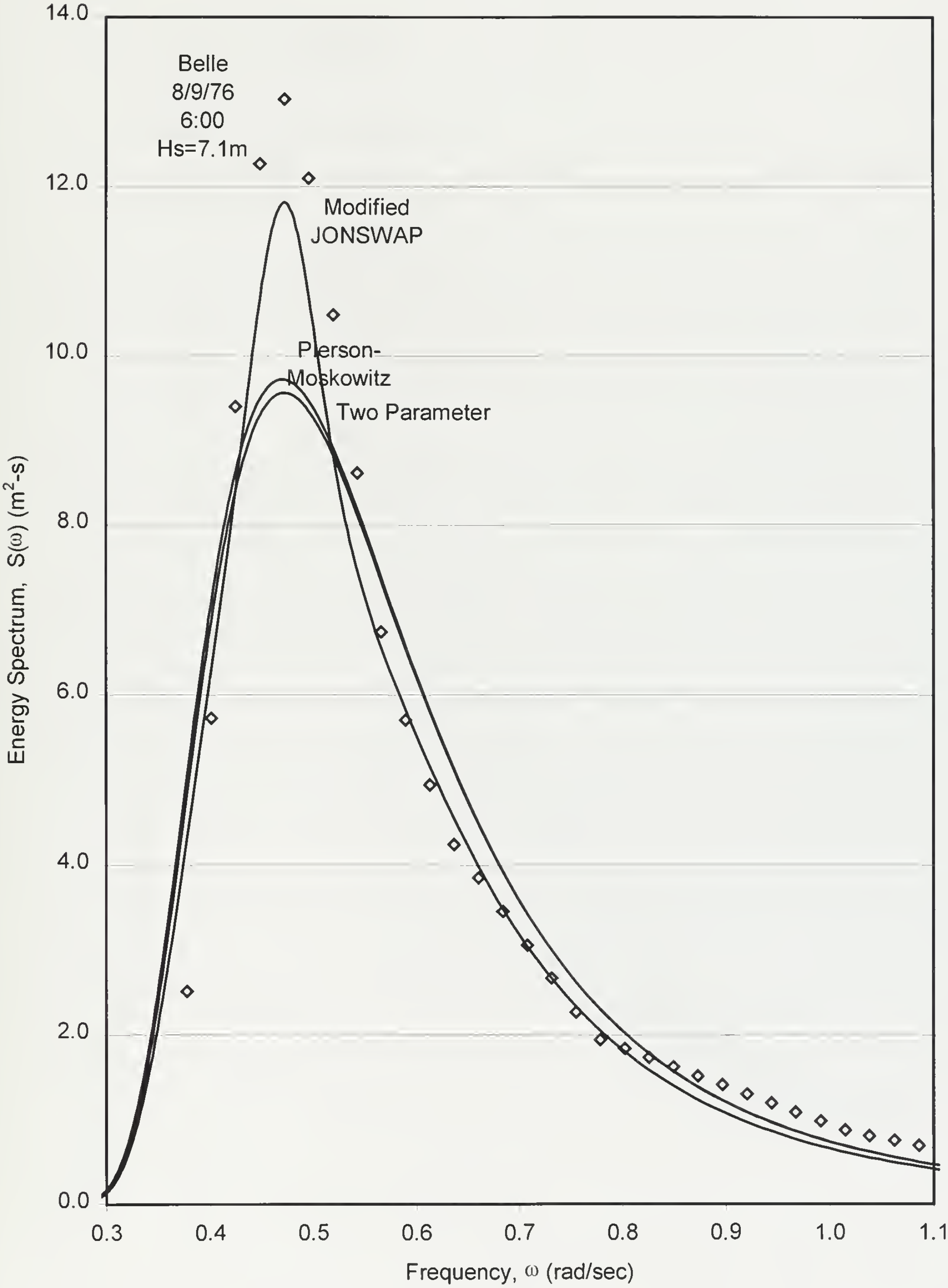

Figure 36 Comparison between Modified JONSWAP and measured spectrum for Hurricane Belle, H_s=7.1 m

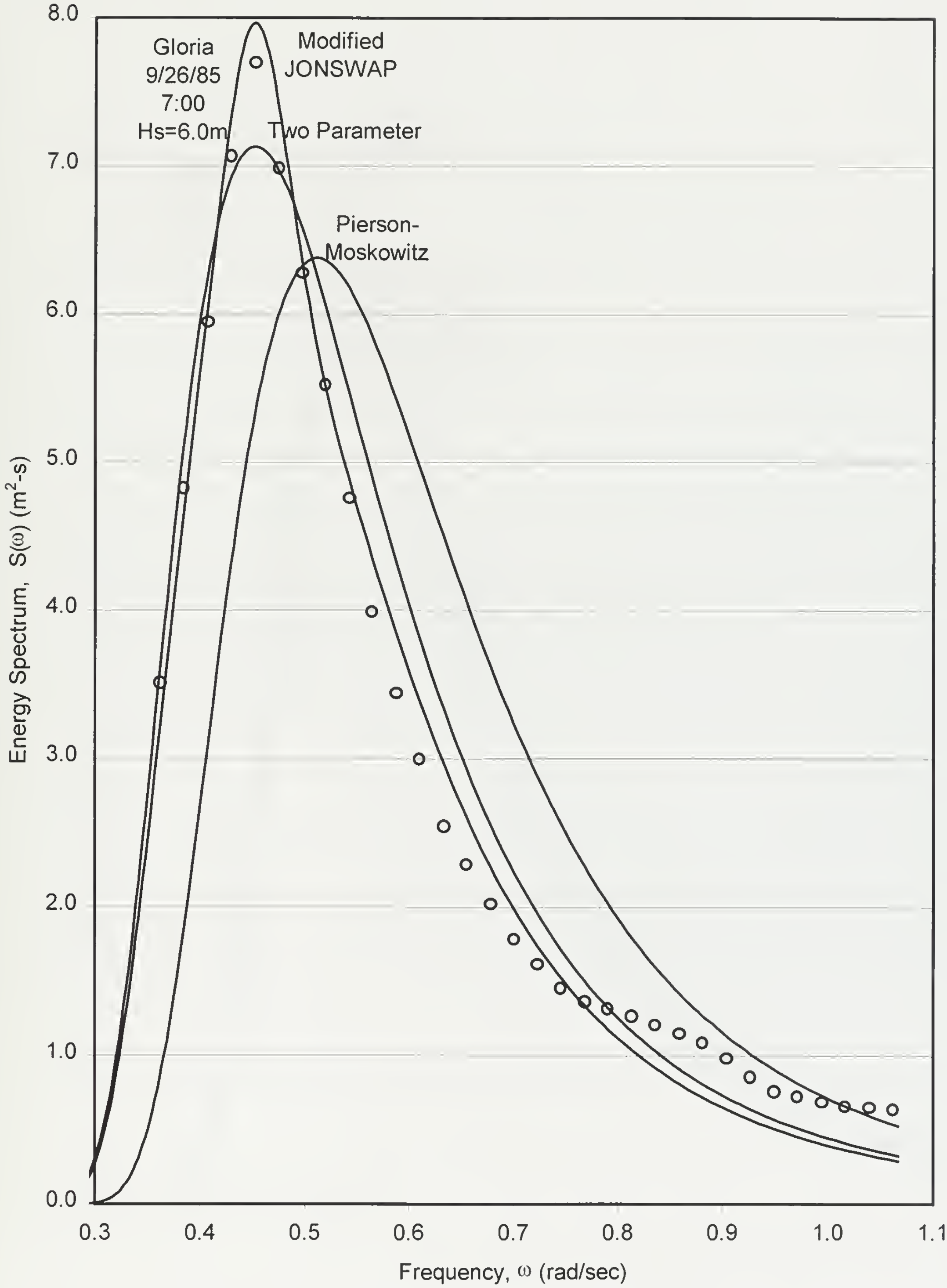

Figure 37 Comparison between Modified JONSWAP and measured spectrum for Hurricane Gloria, H_s=6.0 m

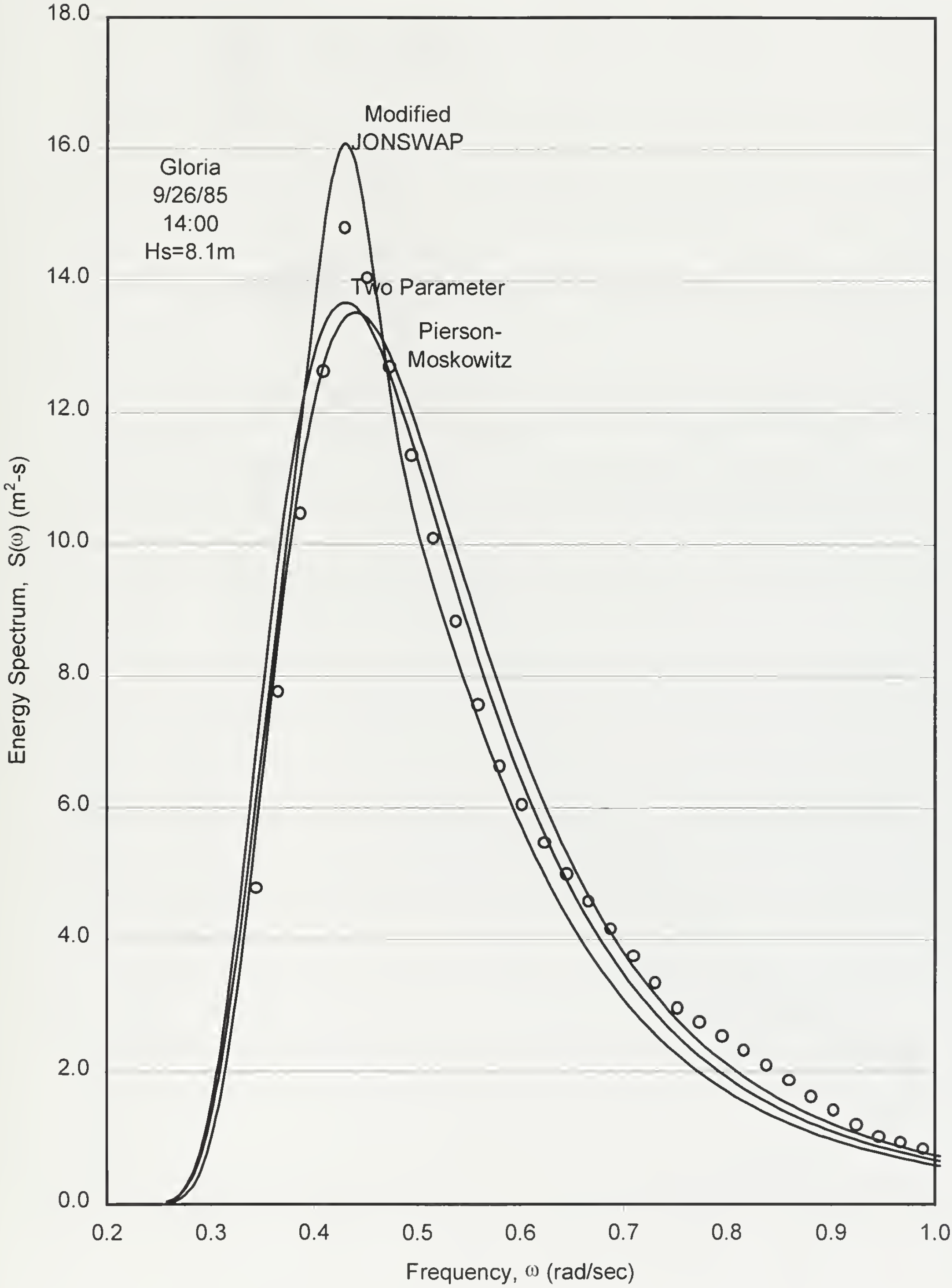

Figure 38 Comparison between Modified JONSWAP and measured spectrum for Hurricane Gloria, H_s=8.1 m

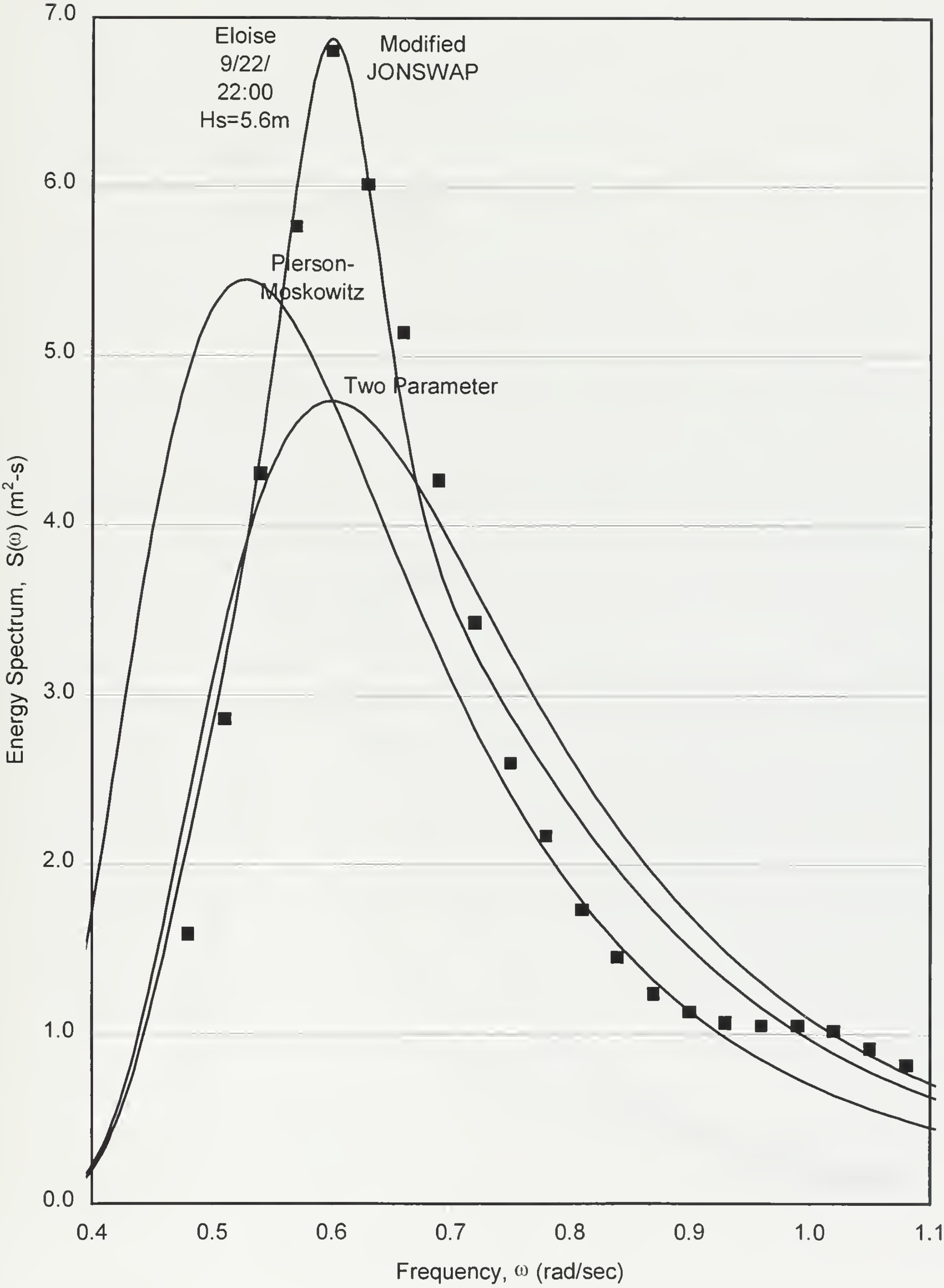

Figure 39 Comparison between Modified JONSWAP and measured spectrum for Hurricane Eloise, H_s=5.6 m

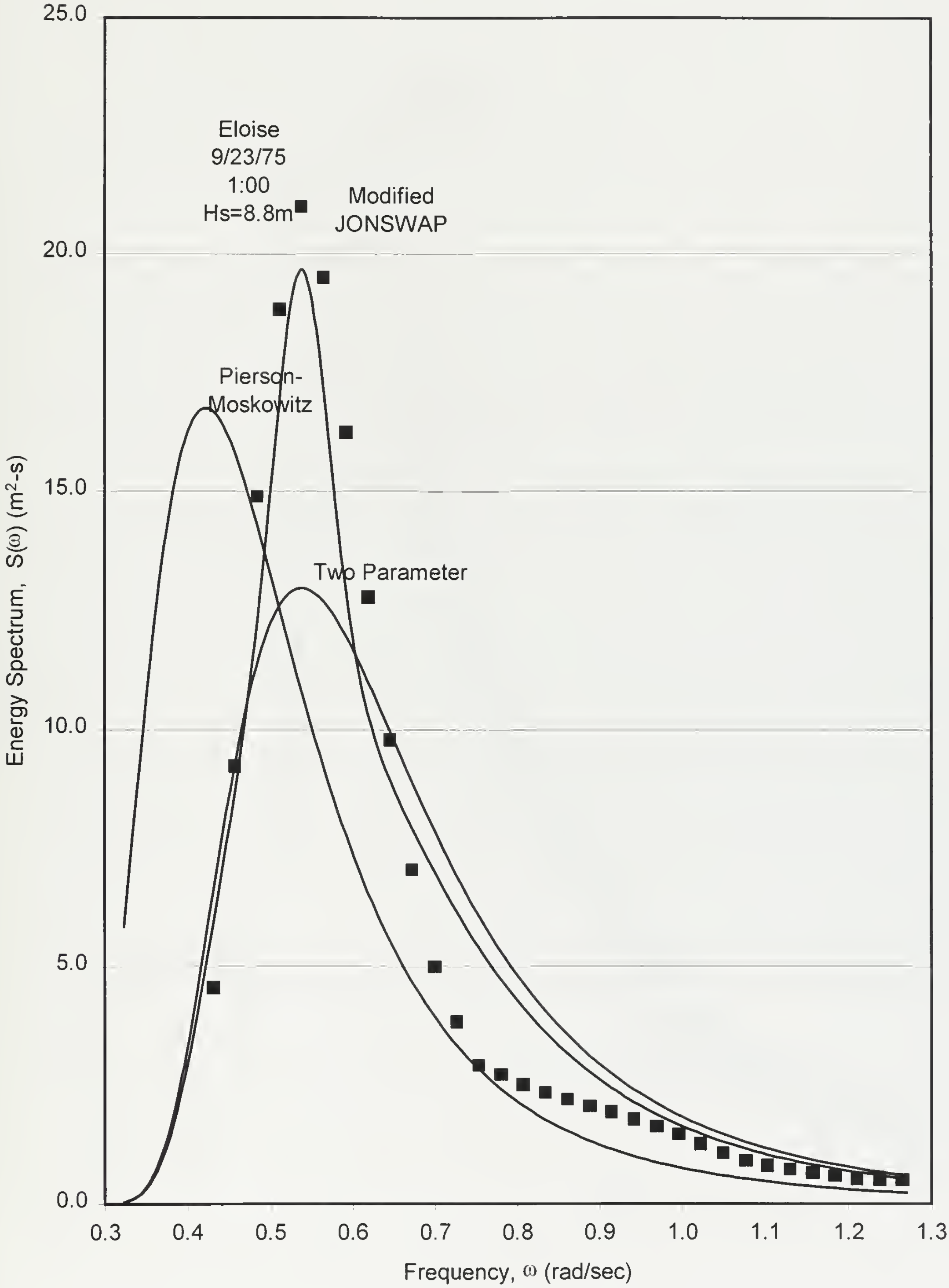

Figure 40 Comparison between Modified JONSWAP and measured spectrum for Hurricane Eloise, H_s=8.8 m

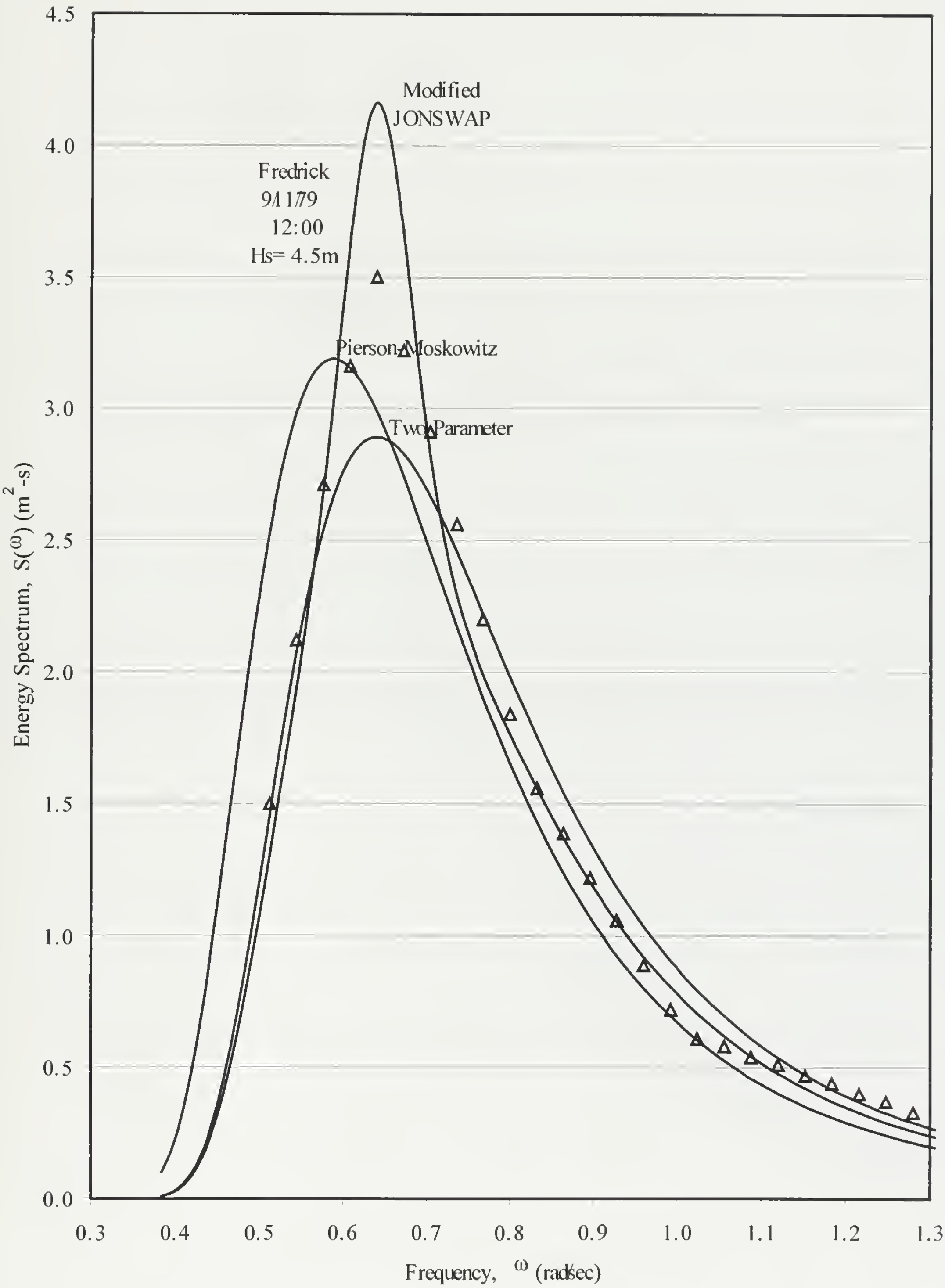

Figure 41 Comparison between Modified JONSWAP and measured spectrum for Hurricane Fredrick, H_s=4.5 m

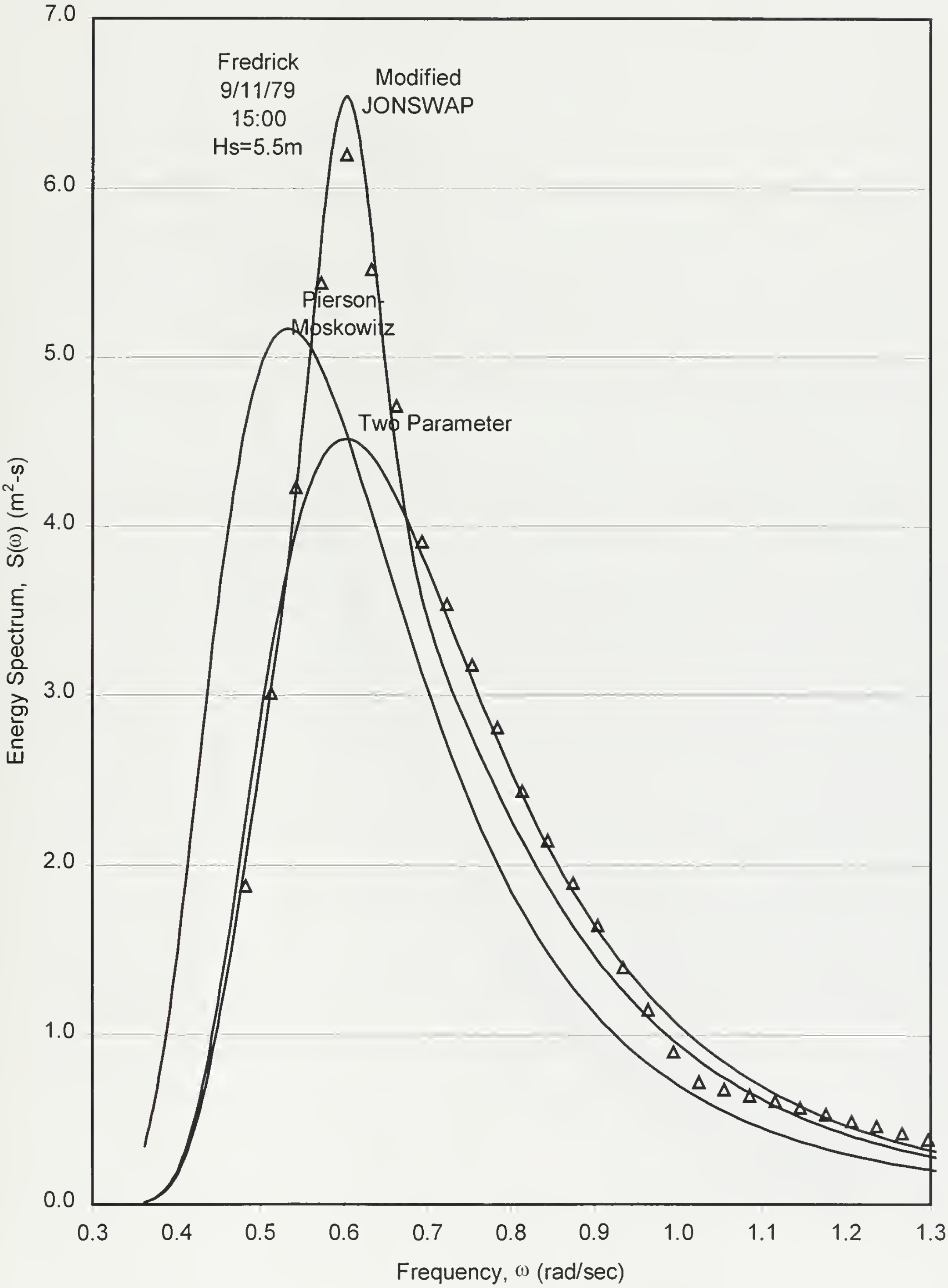

Figure 42 Comparison between Modified JONSWAP and measured spectrum for Hurricane Fredrick, H_s=5.5 m

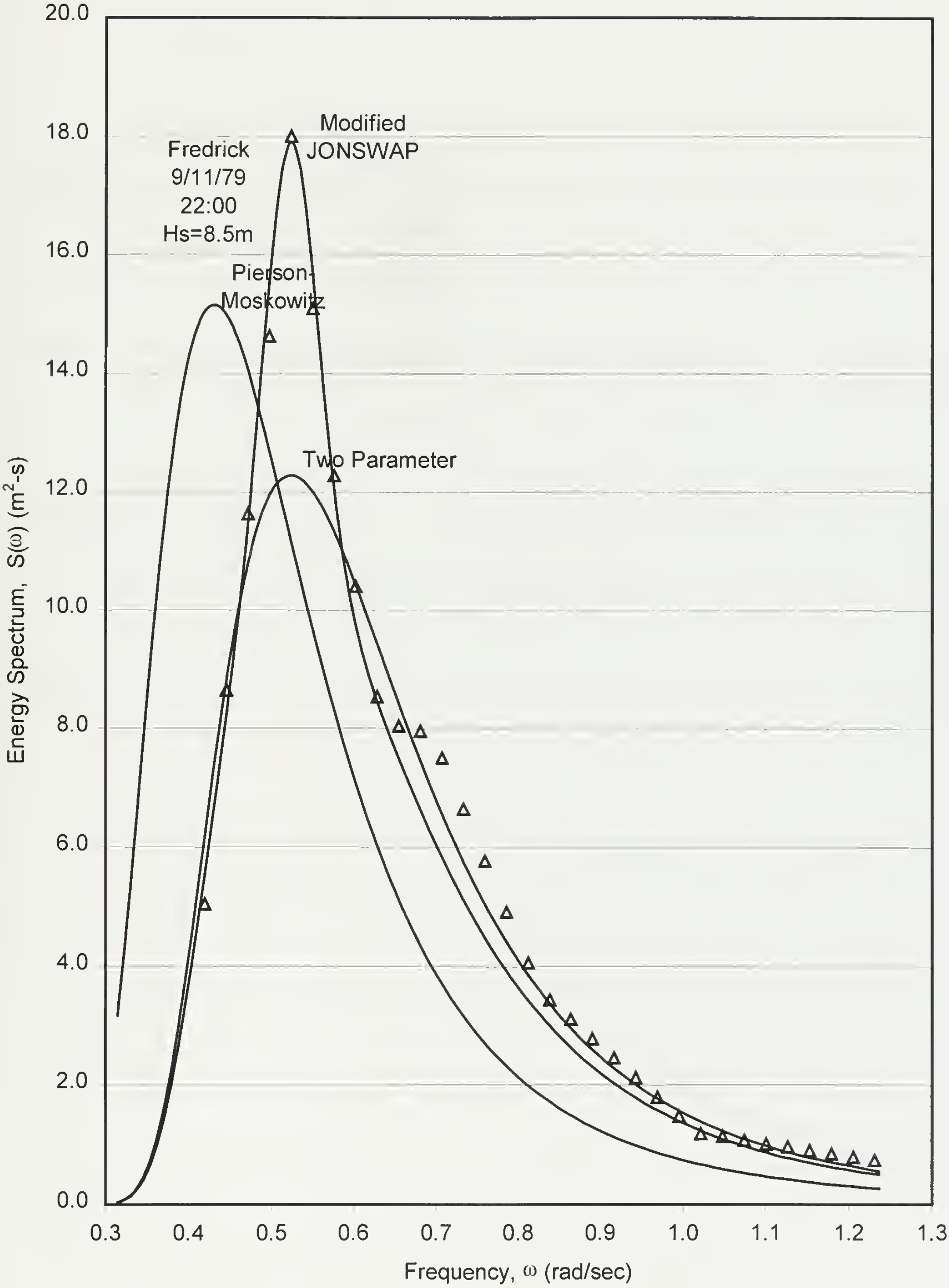

Figure 43 Comparison between Modified JONSWAP and measured spectrum for Hurricane Fredrick, H_s=8.5 m

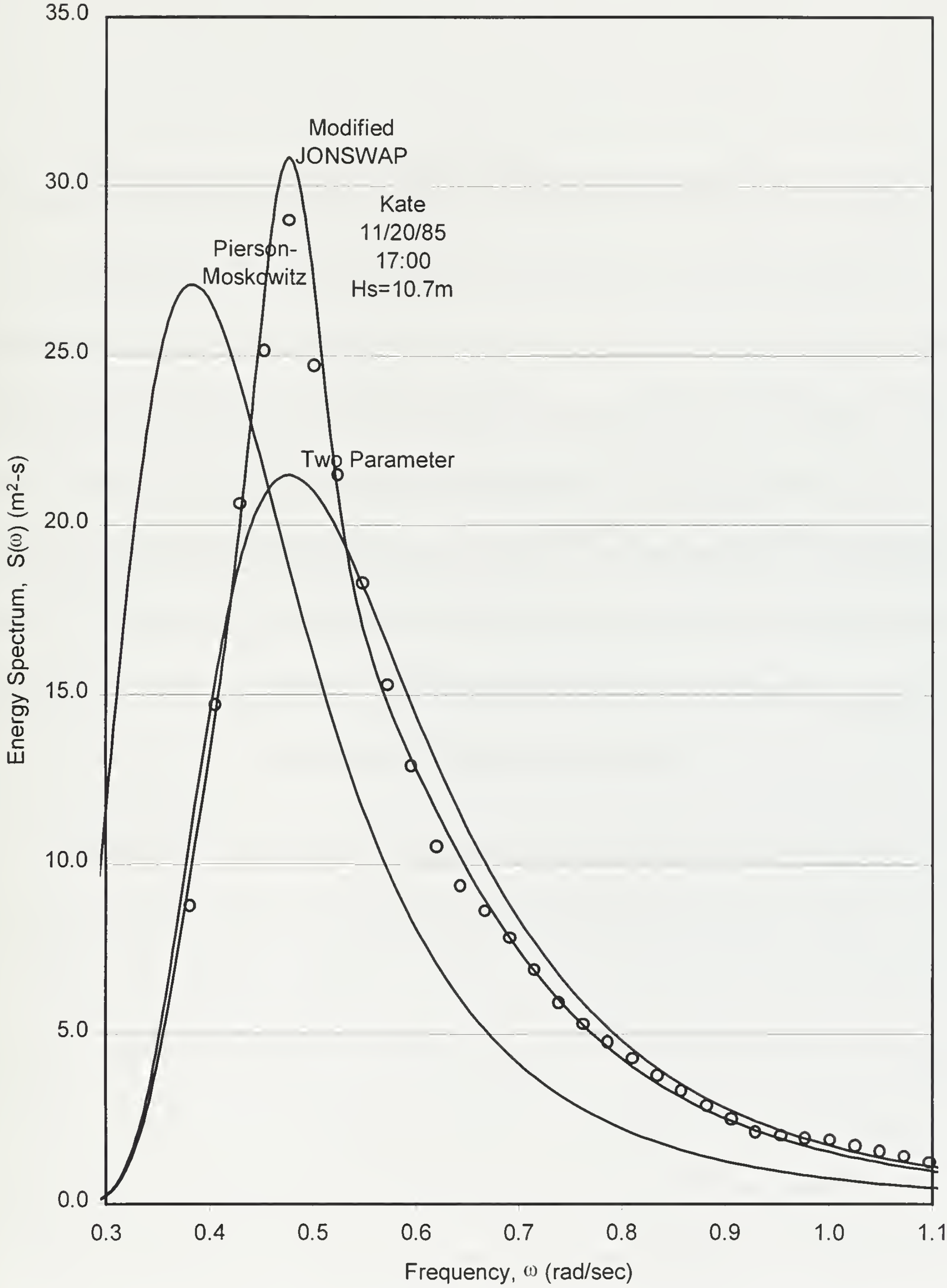

Figure 44 Comparison between Modified JONSWAP and measured spectrum for Hurricane Kate, H_s=10.7 m

CHAPTER 4
ESTIMATION AND PREDICTION OF HURRICANE WAVE SPECTRUM GROWTH

This chapter discusses a method for estimating the growth of sea severity (significant wave height) and modal frequency when a hurricane is approaching a specific location from knowledge of wind speed at that location and distance to the storm. The method will provide significant information for design of offshore structures. As presented in the previous chapter, hurricane-generated are represented by the Modified JONSWAP formula given as a function of significant wave height and modal frequency. For design use, these parameters will be presented in terms of wind speed.

Estimation of significant wave height

Ordinary storms are relatively stationary and associated wind speeds change at a much slower rate and blow over an established quasi-steady fetch length. Wind-generated seas in hurricanes differ from ordinary storms in that the hurricane is moving from 5 to 12 knots with respect to a specific location. This causes a high rate of change of wind speed blowing over a rapidly changing fetch. Ochi (1993) addressed this topic and developed wind speed-sea severity functional relationships for two cases; the growing stage of hurricane-generated seas in which the wind speed is increasing at an extremely high rate but the sea severity was comparatively moderate because the sea condition prior to the hurricane was very mild, the second is the sea condition resulting

from continuous winds of mild severity blowing for one week or longer then followed by a storm, usually a tropical storm which has a wind speed much less then a hurricane.

For an extremely high rate of increase in wind speed following a very mild sea, analysis shows an almost linear increase in sea severity with increase in wind speed. The significant wave height during the growing stage of the hurricane is a function of mean wind speed at a 10-meter level given as Equation (7) and presented in Figure 45.

$$H_s = 0.235U_{10} \tag{7}$$

For a tropical storm following continuos mild winds blowing for one week or longer, sea severity increases rapidly with increase in wind speed. The significant wave height-wind speed relationship seems to be approximated by Equation (8) and is presented in Figure 46. Equation (8) is derived from the Pierson-Moskowitz formulation corrected for a wind speed at a 10-meter height and making a narrow-band assumption.

$$H_s = 0.237\left(U_{10}^2/g\right) \tag{8}$$

Note that the Pierson-Moskowitz spectral formulation is only applicable to fully developed seas. For the sea to become fully-developed at high wind speeds and corresponding large significant wave heights, a significantly long duration is needed (Pierson-Moskowitz, 1964). For example, 42 hours is required for a U_{10} of 20 m/s. Hurricanes do not behave in this manner. Therefore even though the significant wave height-wind speed relationship for the tropical storm close to that given in Equations (8). The shape of the spectrum is different from that of the Pierson-Moskowitz spectrum. For large wind speeds associated with hurricanes, U_{10}>33 m/s, Equation (8) would predict unrealistically high significant wave heights which observation does not support.

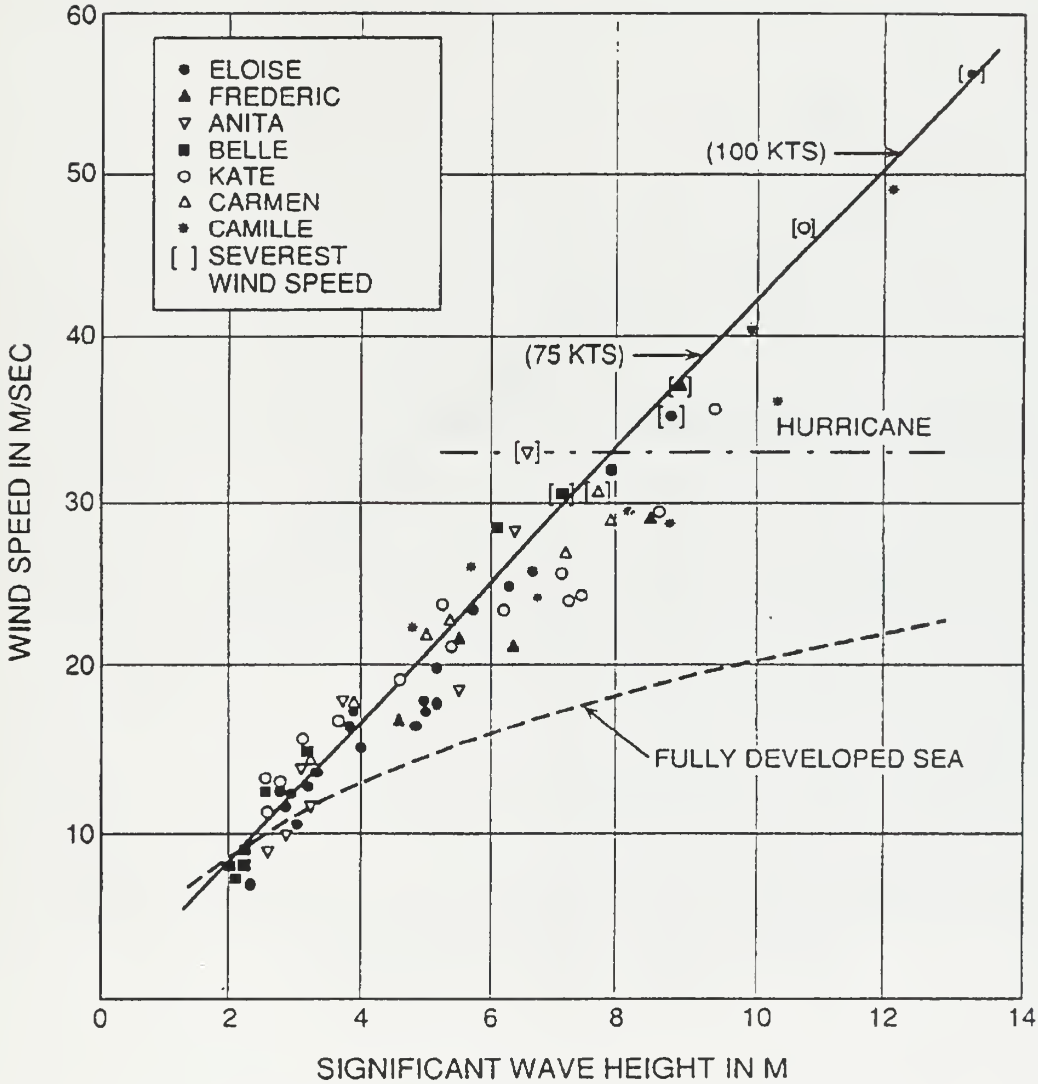

Figure 45 Relationship between mean wind speed and significant wave height obtained in various hurricanes (from Ochi, 1993)

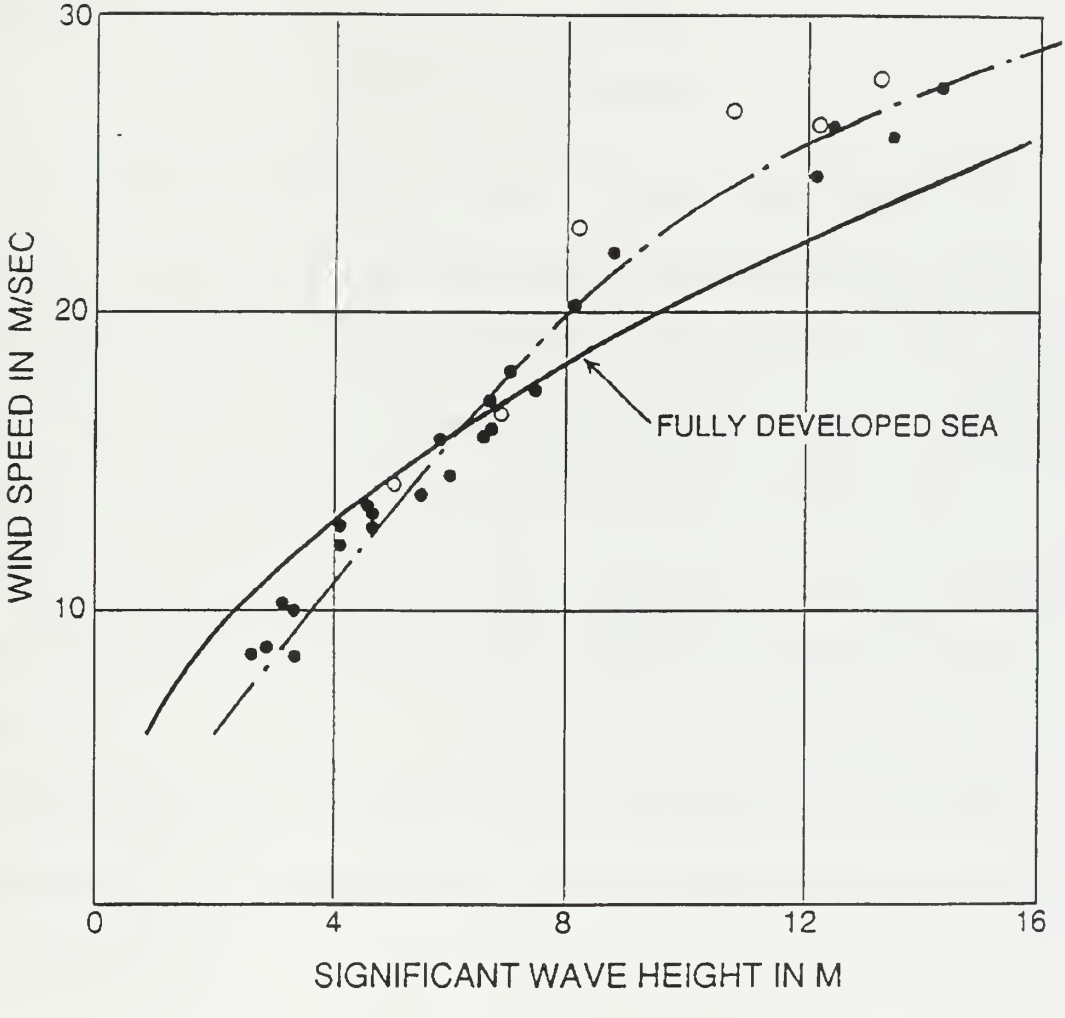

Figure 46 Relationship between mean wind speed and significant wave height, Tropical Cyclone Gloria (solid) (Ochi, 1993) and a North Atlantic Storm (hollow) (Sneider and Chakrabari, 1973

In summary, Equation (7) should be used to estimate significant wave height from knowledge of wind speed at a specified location. Equation (8) applies to specific cases involving tropical storms following several days of steady mild wind. However, it predicts unrealistically high significant wave heights at wind speeds associated with hurricanes.

Prediction of modal frequency

The method given here to predict a trend in change in modal frequency with respect to wind speed is useful in representing growth of hurricane spectra. Unlike for fully developed conditions, where modal frequency is directly related to significant wave height, a modal frequency-significant wave height relationship is difficult to establish for hurricane associated wave spectra. However, a relationship can be found by first estimating the relationship between fetch length and wind speed. Then modal frequency can be estimated through obtaining the relationship between wind speed and modal frequency.

Figure 47 is a plot of fetch length versus wind speed for the various hurricanes considered in this study. It shows a general fetch length wind speed relationship trend given by Equation (9).

$$r = 5.4x10^{7}\,U_{10}^{-2} \qquad (9)$$

At small fetch lengths there is a small but finite wind speed. As fetch length decreases wind speed increases. At large wind speeds fetch length approaches 10 km, a good approximations of the eye diameter, where wind speed is a maximum. Specifying wind speed yields a theoretical fetch length.

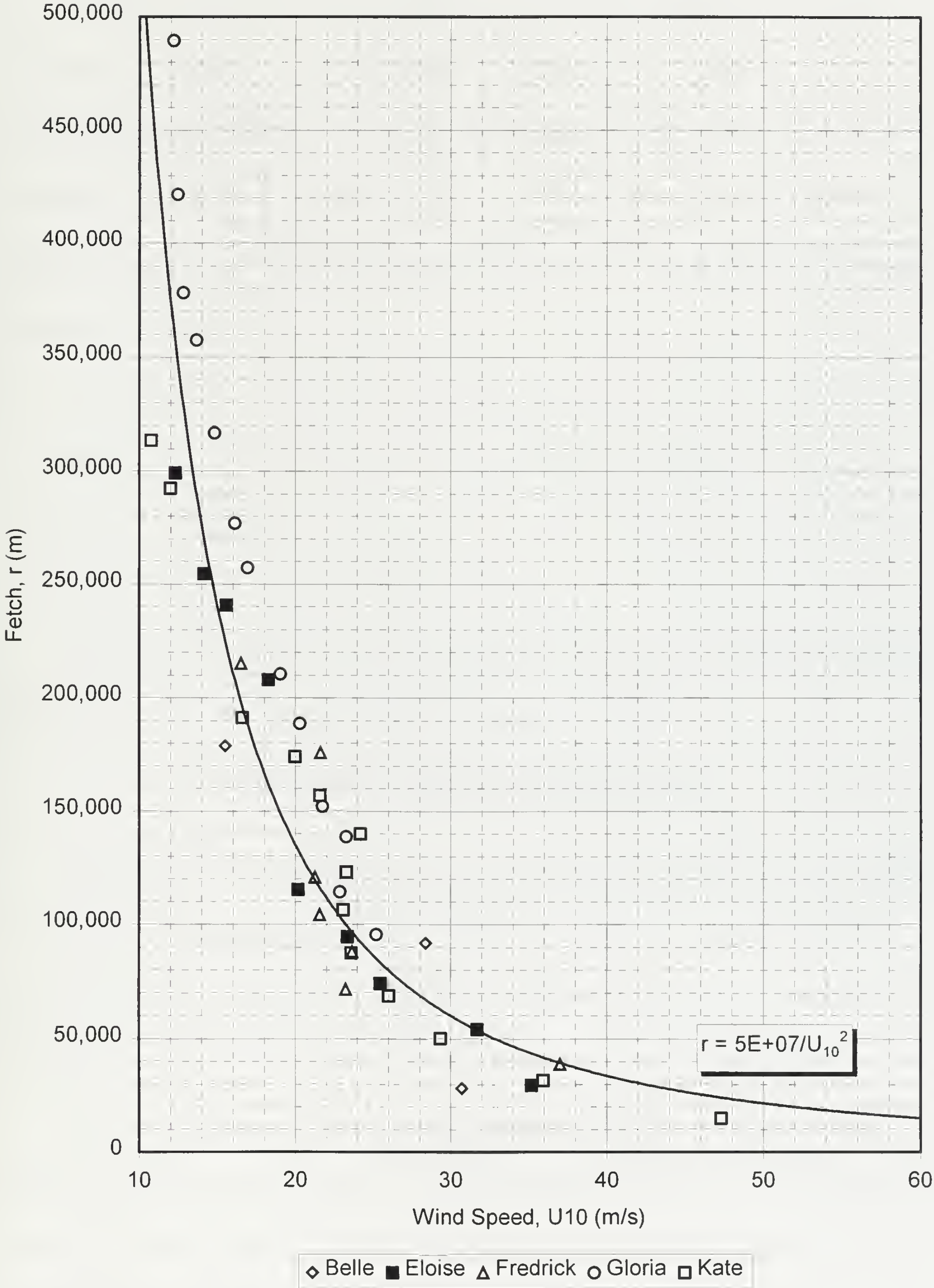

Figure 47 Relationship between mean wind speed and fetch

Next, the relationship between fetch length and modal frequency of hurricane associated wave spectra is discussed. Ross (1976) developed a relationship between the dimensionless modal frequency, υ, and the dimensionless fetch, ξ_r, from the analysis of three storms. This is given in Equation (10). Data considered in the present study compares well to this relationship. Figure 48 is a plot of data and Equation (10), which shows good agreement.

$$\upsilon = 0.97\xi_r^{-0.21} \tag{10}$$

where

$$\upsilon = \frac{\omega_m U_{10}}{2\pi g}$$

$$\xi_r = \frac{rg}{U_{10}^2}$$

Thus, from Equation (9) and (10) it is possible to estimate the modal frequency of hurricane associated wave spectra from knowledge of wind speed.

<u>Estimation of hurricane wave spectrum growth</u>

Hurricane wave energy spectra growth for various wind speeds is now estimated. The following procedure may be used to estimate H_s and ω_m needed for the Modified JONSWAP formula; 1) Specify U_{10}, 2) calculate H_s using Equation (7), 3) calculate r using Equation (9), and 4) knowing U_{10} and r, calculated ω_m using Equation (10).

Figure 49 is a plot of hurricane energy spectrum, $S(\omega)$, for wind speeds from 20m/s to 60m/s and is useful in showing a trend in spectral growth. The plot shows the characteristics of hurricane spectral growth. Modal frequency is concentrated at lower values throughout growth and most growth takes place at the modal frequency.

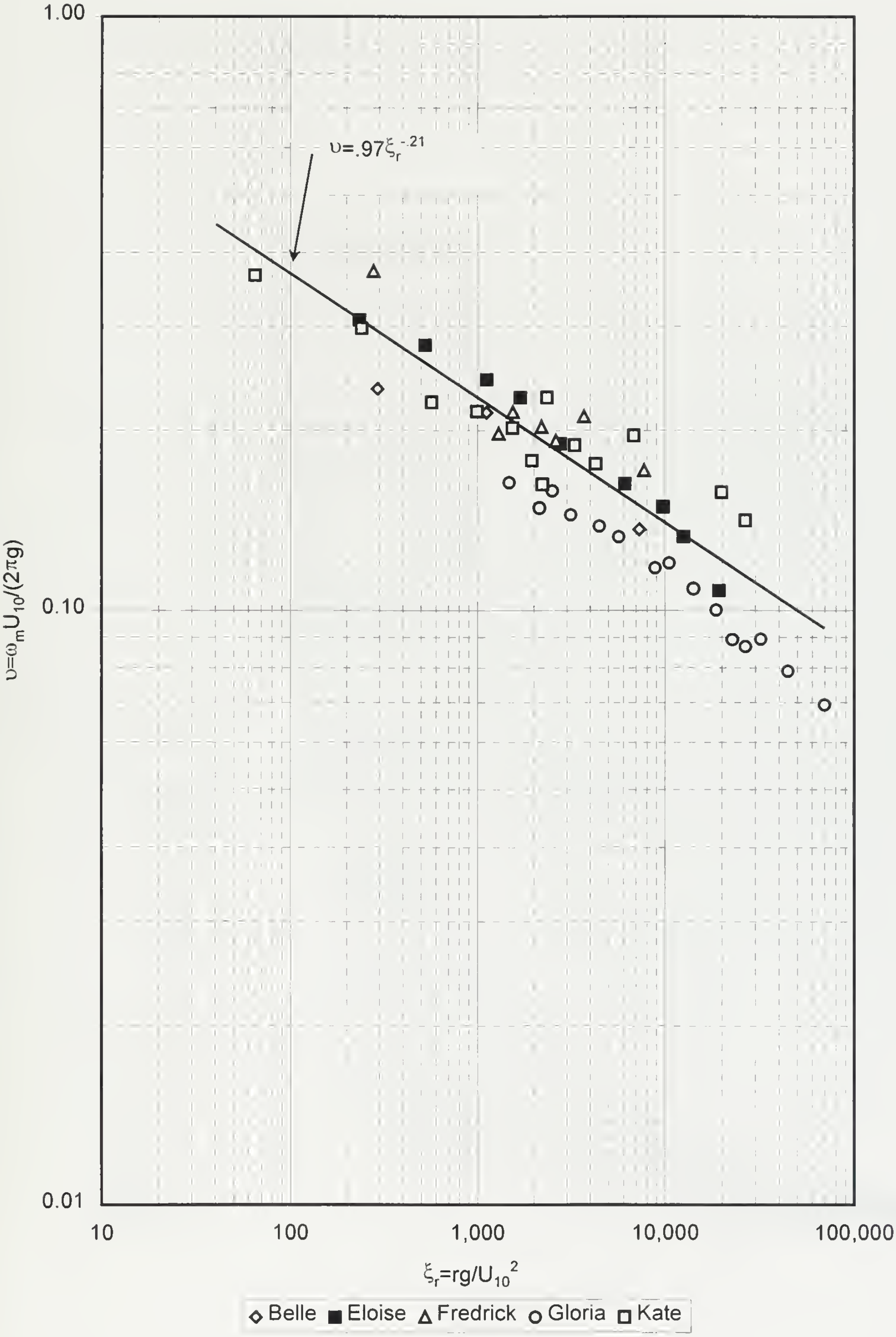

Figure 48 Dimensionless wind speed as a function of dimensionless fetch (based on Ross, 1980)

Figure 49 Predicted hurricane spectrum growth showing mean wind speed and corresponding significant wave height

To show the growth of the wave spectra with respect to significant wave height, the Modified JONSWAP formula is differentiated with respect to significant wave height as,

$$\frac{\partial S(\omega)}{\partial H_s} = \frac{4.5g}{(2\pi)^4} H_s \left(\frac{\omega_m^4}{\omega^5}\right) \exp\left\{-1.25\left(\frac{\omega_m}{\omega}\right)^4\right\} \left(\frac{9.5}{2\pi} H_s^{0.34} \omega_m\right)^{\exp\left\{-\left(\frac{\omega}{\omega_m}-1\right)^2 \Big/ 2\sigma^2\right\}} \tag{11}$$

$$x\left(2 + 0.34\exp\left\{-\left(\frac{\omega}{\omega_m} - 1\right)^2 \Big/ 2\sigma^2\right\}\right)$$

showing growth is proportional to significant wave height at $\omega=\omega_m$ as,

$$\frac{\partial S(\omega)}{\partial H_s} \propto H_s^{1.34}$$

and at $\omega \gg \omega_m$ as,

$$\frac{\partial S(\omega)}{\partial H_s} \propto H_s \ .$$

Clearly, hurricane spectral growth occurs most predominantly at the modal frequency.

CHAPTER 5
CONCLUSIONS

This study dealt with evaluating wave spectra energy growth for hurricane generated seas at various stages of intensities to develop a mathematical formulation representing a trend in the growth of the wave energy spectrum. Since it is difficult to derive a general conclusion by evaluating the difference in the magnitude of energy for a specified wave frequency at different intensities from analysis of spectra obtained from field data, a mathematical formula is needed which represents hurricane wave spectra at various stages of growth. The Modified JONSWAP formula is a good candidate, but needed to be verified over the entire frequency domain. In Chapter 3, it was verified throughout the frequency domain by comparison to hurricane wave spectra from measured data and was shown to represent the wave spectrum associated with hurricane generated seas for various stages of intensity.

The Modified JONSWAP formula is a function of significant wave height and modal frequency. To use it to present a trend in the growth of the wave spectrum, mathematical relationships were presented in Chapter 4 to present significant wave height and modal frequency as functions of wind speed. Using these relationships a plot of the trend in growth of the wave energy spectrum was given for wind speeds of 20 to 60 m/s. The plot shows the characteristics of hurricane wave spectrum growth. Modal frequency is located at lower values throughout and is where most growth takes place.

APPENDIX

DATA

General

The data used for this study were taken from National Oceanographic and Atmospheric Administration's (NOAA) Data Buoys. Atmospheric and oceanographic data has been collected by NOAA Data Buoys since the early 1970's. They are generally located in deep water locations and collect a wide variety of atmospheric and general oceanographic data in addition to wave data. Steele and Johnson (1977) describe the payload and operation of the buoys. There is considerable information at the NOAA world wide web homepage at http://www.nhc.noaa.gov . The data used consists of an hourly energy density spectrum, significant wave height determined by integration, and wind speed for five Atlantic and Gulf of Mexico hurricanes. The purpose of this study is spectral growth, so the data was generally reduced to reflect increasing significant wave height with increasing wind speed. Hurricane path information was obtained at http://www.nhc.noaa.gov/tracks.html . Following are narratives taken from yearly NOAA Mariners Weather Logs for each storm considered.

Hurricane Belle (August 9, 1976) (Mariners Weather Log, 1977)

Belle reached hurricane strength at 1800 on 7 August, 1976 as it moved across the Atlantic in the trade wind belt just east of the Northern Bahamas. Belle's maximum strength was attained on August 9 with sustained winds of 105 knots and a minimum sea

level pressure of 957 mb. While moving northward, parallel to the U.S. East Coast, Belle passed almost directly over NOAA buoy EB15 (32°N, 75.2°W). The largest significant wave height measured was 7.1 m with a wind speed of 30.7 m/s. Belle made landfall on 1000 on August 10 on southern Long Island with sustained winds of 65 knots and minimum pressure of 980 mb. Belle caused tides three feet above normal and four to five inches of rainfall into the mountains of New England. Five fatalities were associated with Hurricane Belle.

Hurricane Eloise (September 22-23, 1975) (Mariners Weather Log ,1976)

The disturbance from which Eloise formed left the African coast on September 6. Winds reached tropical strength early on September 16. Eloise intensified rapidly and reached minimal hurricane strength before it struck the northeastern coast of the Dominican Republic. Fifty-nine deaths occurred in the area, with 34 in Puerto Rico; and damage was estimated at $60 million. Rainfall amounts of 10-20 inches were common over eastern and southeastern Puerto Rico. Eloise weakened as it tracked westward across the mountains of Hispanola and eastern Cuba. By 19 September Eloise was barely a tropical storm as it passed over the Yucatan.

Eloise began a steady strengthening north of the Yucatan Peninsula, regaining hurricane force in the central Gulf of Mexico about 350 miles south of New Orleans on the morning of 22 September. At 0300 on 23 September the eye passed within 10 miles of NOAA buoy EB10 (27.5°N, 88.0°W). The largest significant wave height measured was 8.8 m with a wind speed of 35.1 m/s. It continued to strengthen as it reached landfall midway between Fort Walden Beach and Panama City, Florida, shortly after 1200 on 23

September. A sustained wind near 80 knots with a gust to 135 knots was measured on a 98 foot tower 13 miles offshore. Hurricane tides of 12 to 16 feet were measured. Four deaths in Florida were indirectly attributed to Eloise. The hurricane caused $500 million in loss of property and crops in Florida, Alabama and over the northeastern U.S. due to flooding.

<u>Hurricane Fredrick (September 11-12, 1979) (Mariners Weather Log, 1980)</u>

Fredrick was the first hurricane to strike Mobile, Alabama directly since 1926. The central pressure of 946 mb and maximum sustained winds of 115 knots made Fredrick the most intense hurricane to affect Mobile this century. The highest wind reported in the U.S. was a gust to 126 knots on Dauphin Island bridge in Alabama. The peak storm surge of 12 feet over Gulf Shores, Alabama destroyed most of the Island. An 11 foot surge destroyed the Dauphin Island causeway. Five deaths were attributed to Fredrick. The estimated damage totaled $2.3 billion. Data were obtained from NOAA buoy 42003 (26.0°N, 86.0°W). The largest significant wave height measured was 8.9 m with a wind speed of 37.0 m/s.

<u>Hurricane Gloria (September 25-26, 1985) (Mariners Weather Log, 1986)</u>

Gloria had its start near the Cape Verde Islands on 16 September. On 22 September, hurricane Gloria turned to the northwest as it approached the Leeward Islands. The hurricane weakened as it passed Cape Hatteras after midnight on 27 September. Ten hours later, Gloria crossed western Long Island, New York and emerged back over the open waters of the far North Atlantic. As Gloria again approached the East Coast of the U.S. it passed within 60 miles of the NOAA buoy 41002 (32.3°N, 75.3°W) at

2000 on 26 September. The buoy measured a significant wave height of 14.3 m with a wind speed of 25 m/s.

Hurricane Kate (November 20, 1985) (Mariners Weather Log, 1986)

Development of Kate began just northeast of the Virgin Islands when a weak tropical wave began to interact with an upper air trough on 13-14 November. The tropical storm began moving in a general westerly direction and reached hurricane strength by 1800 on 16 November. Kate moved onto the north central Cuban coast on the 19th and emerged over the waters of the southeastern Gulf of Mexico. It passed the NOAA buoy 42003 (26.0°N, 86.0°W) at 1700 on 20 November. The largest significant wave height measured was 10.7 m with a wind speed of 47.3 m/s. Kate weakened slowly before making landfall near Mexico Beach, Florida on 21 November.

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BIOGRAPHICAL SKETCH

William Scott Finlayson was born on December 27, 1969, in Alamogordo, New Mexico and grew up in Arizona and New Mexico. He attended New Mexico State University in Las Cruces and received a Bachelor of Science degree in mechanical engineering in May 1991. He entered the Navy through the Navy Civil Engineer Collegiate Program in 1989 and received his commission through Officer Candidate School in Newport, Rhode Island, in November 1991.

After attending Civil Engineer Corps Officer School in Port Hueneme, California, he was assigned to Marine Corps Air Station Iwakuni, Japan as the Facilities Maintenance Officer and later as the Maintenance Control Officer, from April 1992 through April 1994. LT Finlayson reported to Naval Mobile Construction Battalion SEVEN, Gulfport, Mississippi in April 1994 and served as Officer in Charge for Details deployed to Sasebo, Japan, and El Salvador. He was assigned to the University of Florida in September 1996 as part of the Civil Engineer Corps Ocean Facilities Program of the United States Navy and will received a Master of Science degree in coastal and oceanographic engineering in December 1997.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Michel K. Ochi, Chairman
Professor of Coastal and Oceanographic Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Ashish J. Mehta
Professor of Coastal and Oceanographic Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

D. Max Sheppard
Professor of Coastal and Oceanographic Engineering

This thesis was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Master of Science.

December, 1997

Winfred M. Phillips
Dean, College of Engineering

Karen A. Holbrook
Dean, Graduate School

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